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Manpower Cost Reduction in Electronics Maintenance: Framework and Recommendations

Gary R. Nelson, Robert M. Gay and Charles Robert Roll, Jr.

A Report prepared for
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



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PREFACE

This report was prepared as part of Rand's DoD Training and Manpower Management Program, sponsored by the Human Resources Research Office of the Defense Advanced Research Projects Agency (ARPA). Manpower issues are assuming increased importance in defense planning and budgeting, and it is the purpose of this research program to develop some broad strategies as well as specific solutions for dealing with present and future military manpower problems. This includes the development of new research methodologies for examining broad classes of manpower problems, as well as specific, problem-oriented research.

The present report was developed in response to a request from the recently formed Electronics Management Steering Group in the Office of the Director of Defense Research and Engineering. The Steering Group asked for a study of possible alternatives for reducing the personnel-related costs of electronics maintenance, which are rapidly rising. They specifically asked that job performance aids be evaluated. The purpose of this study was to assist managers in OSD and the services by making specific recommendations for research that would lead to a reduction of electronics maintenance costs.

The recommendations reported here were developed during a four-week study conducted at Rand in late 1973. A major contribution of this report is to show that alternatives for reducing manpower costs in electronics maintenance must be considered within a broader framework. Because of the time limitation, the resulting specific recommendations are concentrated in areas where the data were most readily available--Air Force electronics and, particularly, avionics--but they are broadly applicable to other electronics systems as well.

SUMMARY

The costs of maintaining military electronics systems have increased sharply in recent years. Two major sources of this increase can be identified. First, electronics systems have become much more numerous and complex, and second, personnel costs have risen sharply--especially the cost of first-term enlisted personnel. This report looks at methods of reducing these costs.

Recommendations are made in three subject areas: maintenance manning, job performance aids, and the personnel and training system. In addition, we have distinguished between short-term experiments or demonstrations that could be completed in six months to one year and longer-term projects. The areas in which recommendations are made, of course, are not independent of each other. Recommendations for reducing personnel-related costs of electronics maintenance must be put in a broader context to avoid myopic solutions which reduce personnel costs but increase other costs or reduce military capability. Three questions must be resolved simultaneously to ensure efficient provision of national defense:

1. What quantities and types of weapons systems should be procured?
2. At what level should these systems be maintained?
3. How should the level of maintenance be provided?

The recommendations in this report deal largely with the third issue--principally because this is most directly responsive to the request made by the Steering Group. However, a framework is presented for analyzing maintenance decisions in a broader context. Such a perspective is essential to selection of efficient maintenance policies.

Selected recommendations from the body of the report are presented below.

SHORT-TERM DEMONSTRATIONS AND EXPERIMENTS

Maintenance Manning Policies

Efforts should be made to identify those electronics subsystems used by both the military and commercial carriers and to make comparisons of maintenance practices and costs. In particular, the Carrousel inertial navigation system developed by General Electric should be studied.

Data on the costs of contractor depot repair of recent electronics systems should be compared with regular military depot repair costs where possible. The N-16 and Kearfott-Singer ASN-90 inertial navigators are two systems that might be compared.

Comparisons should be made, where possible, of field and depot re-test OK rates and failure rates after repair. These should be used to evaluate the relative diagnostic and repair capabilities at the base and depot levels. For example, the integrated display on the F-111D and the inertial measurement set on the A-7D are possible candidates for study.

Job Performance Aids

In view of the importance of large-scale demonstration of Job Performance Aids (JPAs) and the long start-up time involved in such demonstration, the Air Force should provide funding to expand the scope of the on-going AFHRL study to compare alternative types of technical documentation.

The introduction of the PIMO (Presentation of Information for Maintenance and Operations) system of job aids for the C-141A should be monitored and evaluated to permit comparisons of maintenance costs and measures of productivity or maintenance efficiency with and without the JPA system. Planning and data collection for monitoring and evaluating the new system should begin immediately.

The development of job aids for the AQA-7 sonar subsystem should be followed up with field tests. The Navy should ensure that the field tests are properly conducted, using control groups and collecting data on maintenance costs and performance for the sonar subsystem as well as on mean times to repair and other statistics for individual technicians.

The decision to cease development of the integrated job aids for the AWG-10 should be reconsidered by the Navy. If development is recommended, plans should be made to make the job aid system operational as soon as possible. Again, securing base-line data and creating proper control groups should accompany introduction of the system.

DoD should examine commercial aviation troubleshooting systems, such as the FEFI/TAFI system developed by Douglas for the DC-10, for possible military applications.

LONGER-TERM DEMONSTRATIONS AND EXPERIMENTS

Maintenance Manning Policies

Continual and systematic performance testing of random samples of enlisted men should be undertaken to estimate the productivity of individuals and the factors influencing it. This testing should begin with the largest electronics career fields because potential savings are greatest there and because large samples increase the reliability of statistical estimates. The following career fields should be included: Army, Tactical Electronic Equipment Maintenance (EE) and Air Defense (AD); Navy, Electronics Technician (ET) and Aviation Electronics Technician (AT); Marines, Avionics (62); Air Force, Communications Electronics Support (30) and Avionics Support (32).

Research should be undertaken to develop models of military units and to validate the models and apply them to the evaluation of manning standards. The possibility of basing manning standards on data and programs already in existence should be seriously considered. Research should be conducted using simulation models and other methods to develop productivity weights for personnel with differing amounts of experience.

Job Performance Aids

Fully proceduralized job performance aids (FPJPAs) for non-troubleshooting tasks should be considered, especially for maintaining high-cost equipment now in the inventory. A review should be undertaken to determine if maintenance costs can be reduced significantly by improved performance of routine maintenance. (FPJPAs should be

developed from the same specifications and for the same sets of tasks as listed below.)

Non-troubleshooting job guide manuals should be developed for all new equipment. They should cover the tasks of checkout, adjustment, alignment, and calibration and should be developed using the draft specification in TR 73-43, formulated by AFHRL.

JPA's for new weapons systems should be procured at the same time as the system itself. The operational testing period for the new system should be used to validate and revise the JPA's.

In those areas where JPA's are introduced, technical training should include instruction in the use of these aids, and incentives should be provided to encourage their use.

DoD and the services should seek ways to support the JPA concept in the weapons system procurement process. For a period of two to three years DDR&E and OSD/I&L should review the specifications and funding for technical documentation for new weapons systems. The services should provide special funding for new types of JPA's within a separate program element.

Further development of computer-generated, fully proceduralized troubleshooting aids (FPTA's) should be supported, and research efforts should be directed toward developing FPTA's that help evaluate the maintenance rates of equipment.

An expanded research program should be undertaken for JPA's, with emphasis on aids for troubleshooting, to determine which types of troubleshooting aids are most useful to the repairmen. Such an effort was initially proposed by AFHRL and should be funded as part of their research program.

DoD should attempt to estimate the incremental costs of developing more elaborate systems of JPA's for various types of electronics systems. The costs should be estimated for several different sets of aids for each system. The costs should reflect the assumption that the aids would be prepared under the new draft specification TR 73-43 formulated by AFHRL. These estimates should provide a rough gauge for estimating costs of JPA's for new systems.

In exploring the economic aspects of JPAs, DoD should investigate the cost and potential benefits of developing families of job aids for electronics equipments. These aids would provide appropriate types of assistance to personnel of different skill levels.

Personnel and Training

In fields of electronics specialties, where the equipment is highly diversified, the services should consider increased on-the-job training to replace the instruction given with generic equipment in technical schools.

The military services should reevaluate the military specialty code system in light of the diversity of electronics systems. For electronics specialties that maintain highly diversified types of equipment the services should consider using additional occupational identifiers to indicate which equipment an individual is qualified to maintain. The identifiers can be used in assigning personnel to units. For troublesome electronics systems, this process would ensure that only capable personnel were given responsibility for maintaining a given system; repairmen with the same specialty code but unfamiliar with the particular system would not be rotated in as replacements.

The military services, particularly the Army and the Air Force, should evaluate the benefits of employing a more senior force of electronics technicians, perhaps by measuring the productivity of personnel with different levels of experience. A more experienced force of technicians can be achieved by raising first-term reenlistment rates through increases in special pay or by requiring an extended initial term for personnel serving in the electronics area. This, of course, would raise the average cost per man, but the greater effectiveness of senior personnel in such difficult areas as troubleshooting could result in a requirement for fewer maintenance personnel and could thereby reduce total costs.

ACKNOWLEDGMENTS

Our efforts to develop some recommendations to reduce electronics maintenance costs have benefited from the contribution of a number of persons. Those who played a major role in discussions and plans for this report, and who have in some cases contributed written sections, include M. B. Carpenter-Huffman, D.S.C. Chu, R.V.L. Cooper, G. C. Haggstrom, P. Y. Hammond, D. W. McIver, and R. Shishko, all of The Rand Corporation. Ross D. Morgan of the Air Force Human Resources Laboratory and John D. Folley, Jr., of Applied Science Associates provided consulting help. The authors also benefited from conversations with Thomas C. Rowan; many of the recommendations endorsed in this report came from Rowan's earlier report on job performance aids. In addition, the authors were able to consult with Rand's experts in the electronics, maintenance, and training areas--specifically, I. K. Cohen, D. C. Gogerty, M. R. Fiorello, J. R. Nelson, R. M. Paulson, and H. Shulman. Finally, we would like to thank R. E. Park and M. R. Fiorello for their helpful criticism.

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I. INTRODUCTION

In response to an increasing concern within the defense community and the Federal Government with procurement and life-cycle costs of DoD electronics equipment, an Electronics Management Steering Group has been formed in the Office of the Director of Defense Research and Engineering (ODDR&E). The purpose of the Steering Group is to develop and recommend to the Secretary of Defense methods of reducing the costs of procurement and maintenance of electronics equipment. The Steering Group may recommend either management or R&D approaches to meeting this objective. The purpose of this report is to analyze some of the manpower and personnel aspects of the electronics maintenance problem and to develop recommendations that will result in reduced maintenance costs for electronics systems. In seeking to accomplish its mission, the Steering Group has identified various tasks and assigned these to the services and to ARPA. Rand's effort directed at this problem is in response to the task imposed on ARPA by the Steering Group. ARPA was asked to prepare a paper which would (a) detail experiments or demonstrations that could be conducted on a reasonably large scale and in the short term to demonstrate the utility of job performance aids (JPAs) and of new approaches to maintenance training or to offer other suggestions to reduce the personnel costs inherent in electronics maintenance support, and (b) develop general recommendations and a rationale for research programs designed to reduce personnel-related costs in electronics maintenance.

DoD's concern with the cost of acquiring and maintaining electronic systems can be traced to two sets of factors, although undoubtedly there have been other influences on the particular timing of a major effort to reduce costs in the area of electronics. The first set of factors has been DoD's recent experience principally with the accelerating costs and maintainability problems of new electronics systems. (Recent trends and developments in the area of electronics systems are outlined below.) The second set of factors underlying the special effort to reduce electronics costs is related to the growing tightness of the defense budget, a situation which has been made worse by the growth in manpower costs.

With the advent of a volunteer armed force, rising manpower costs,^{*} and tight defense budgets, military manpower has become one of the most important issues in defense planning and budgeting. Manpower costs have risen dramatically in recent years, both in total dollars and in the proportion of the U.S. defense budget they consume. For example, personnel-related costs for defense increased by 100 percent between 1962 and 1972. In 1962, military manpower costs constituted 43 percent of the total U.S. defense budget; the 1972 figure was 54 percent.^(1,2) Furthermore, whereas manpower costs are expected to continue to increase, the total U.S. defense budget is expected to stay roughly constant in real terms for the foreseeable future. These trends have caused attention to be focused on finding ways to reduce manpower costs across the entire spectrum of defense activities, and, while electronics maintenance costs are the prime concern here, policies that are effective in reducing these costs may be effective in other areas as well.

This report looks at ways to reduce electronics maintenance costs from a manpower and personnel perspective. We consider not only job performance aids, but maintenance manning, personnel policies, maintenance training, and procurement policies for electronics systems as sources of potential savings in the cost of electronics maintenance. The following subsection briefly discusses electronics maintenance, and some recent trends and developments, as a way of introducing the electronics maintenance problems and providing a background for the analyses and recommendations presented in this report.

TRENDS AND DEVELOPMENTS IN ELECTRONICS SUPPORT SYSTEMS

Maintenance activity in the military occurs at three levels: organizational, intermediate, or depot. Organizational maintenance is provided by the unit in the field or on the flight line, intermediate maintenance may also be provided by the operational unit, but usually in a shop context, and depot maintenance typically occurs at centralized maintenance facilities. The level of maintenance activity is important because it determines the type of personnel who perform the maintenance. Organizational and intermediate maintenance, to the extent that it is provided by the operational units, is performed almost exclusively by

^{*} Manpower costs are defined as the sum of total military pay and allowances, civilian pay, and military retirement pay.

military personnel. At these maintenance levels the problems common to military personnel often arise: training, utilization, rotation, and retention. Repairmen at depots and at centralized laboratories, however, tend to be civilian technicians. In addition to these government employees, technicians employed by the manufacturers of electronics components must also be counted as part of an extended logistics system. Turnover rates tend to be considerably lower among civilian and contractor technicians than among military personnel; therefore, there are fewer personnel undergoing training and fewer apprentices to be assisted by JPAs. The characteristics of the maintenance activity also differ between military repair personnel at the unit and civilians at the depot. Organizational and intermediate maintenance for electronics comprises primarily fault isolation and component replacement rather than the repair of faulty parts.

Aggregate Maintenance Costs

Electronics maintenance is a costly activity for the Department of Defense. Although progress has been made by the services in recent years in predicting maintenance costs for particular systems, estimates of the aggregate cost of maintaining electronics systems remain something of a guess. A Defense Science Board report estimates that electronics maintenance is one-quarter of the fiscal 1974 operations and maintenance budget, or about \$5.6 billion.⁽³⁾ The source of this estimate is the Electronics X study at the Institute for Defense Analyses, which has developed other estimates of electronics maintenance costs ranging from \$3 to \$8 billion. By a rather conservative set of assumptions, Rand has estimated the cost of maintaining avionics alone at \$1.5 billion for the Air Force and \$2.0 billion for the DoD as a whole.* An estimate can be made of the magnitude of military manpower costs in this area by considering maintenance personnel. There were 241,592 enlisted personnel on active duty at the end of fiscal 1972 with an occupational designation of electronics maintenance (DoD Occupational Code 1). Table 1 gives the breakdown of these personnel by branch of military service.

* J. F. Digby, unpublished work, The Rand Corporation.

Table 1
ELECTRONICS EQUIPMENT REPAIRMEN, DOD OCCUPATIONAL CODE 1
(As of June 30, 1972)

Service	No. of Personnel	Total No. Enlisted	Percentage in Electronics
Army	76,288	686,695	11.1
Navy	69,459	510,669	13.6
Marine Corps	13,772	178,395	7.7
Air Force	82,073	599,774	13.7
Total DoD	241,592	1,975,533	12.2

SOURCE: OASD/M&RA, June 30, 1972.

Military pay and allowances and other personnel costs are roughly \$10,000 per man per year. Also, training costs in this area are quite high; in the Air Force, formal school training costs are reported to be in the neighborhood of \$10,000 per man.* Assuming an annual turnover rate of 25 percent in the electronics field, the total cost per man is \$12,500 per year. This would give a total annual cost of military personnel in electronics maintenance of around \$3.0 billion. To this figure must be added the cost of civilian maintenance personnel, the cost of spare and replacement parts, and a share of overhead costs.

Electronics Systems Maintenance Costs

Given the problems of obtaining a single aggregate estimate of electronics maintenance costs, an accurate time series is probably impossible to obtain. Some indications of the likely cost trend can be seen in the procurement costs of electronics systems. A study at Rand, which is now somewhat out of date, showed that the procurement cost of electronics systems took only 11 years to increase by a factor of ten.† In a sense this figure may be misleading, since the military services have tended

* Training costs do include instructor costs, many of whom would be military personnel already included in Table 1, but the cost of on-the-job training is not included (see Ref. 4).

† See Ref. 5, p. 3.

to purchase fewer aircraft of the more recent, more expensive vintages-- in effect, have attempted to substitute quality for quantity. Nevertheless, the development of complex, highly integrated electronic systems has created unique maintenance problems. As a result, on some of the later aircraft, three of the approximately 100 different system (avionics, propulsion, fuselage) have absorbed a major portion of the chargeable maintenance costs. The Air Force's Improved Reliability of Operational Systems (IROS) cost system gives maintenance cost estimates for specific systems.* Table 2 shows IROS cost estimates as a percentage of total maintenance costs for the three most expensive subsystems on five currently operational weapons systems. In each case at least two of the three systems are avionics.

Table 2
IROS COSTS FOR OPERATIONAL WEAPONS SYSTEMS

Weapon System	Three High-Cost Subsystems	Percent of IROS Cost
A-7D	Inertial Measurement Set	14.8
	Forward-Looking Radar	11.2
	Launch and Racks	5.3
		<u>31.3</u>
F-111A	Inertial Navigation System	11.8
	Attack Radar Set	9.5
	Fuselage	6.6
		<u>27.9</u>
F-111D	Integrated Display	46.8
	Attack Radar Set	17.0
	Inertial Navigation Set	6.0
		<u>69.8</u>
F-4C	Inertial Navigation System	9.7
	Attack Radar Set	8.3
	Fuselage	5.9
		<u>23.9</u>
F-4E	Attack Radar Set	12.7
	Inertial Navigation Set	10.0
	Fuselage	4.7
		<u>27.4</u>

* IROS provides a method of estimating logistics support costs at quite detailed levels. It includes labor charges from both the unit and the depot (adjusted to reflect overhead) and the cost of replacement parts.

New Fault Isolation Environment

Some recently developed avionics systems have radically affected the tasks of fault isolation and repair as traditionally performed by electronics maintenance personnel. In the A-7D, the Mark II avionics on the F-111D, and in other recent systems, the avionics systems have become highly integrated. An on-board computer accepts signals from the avionics components, and interprets, integrates, and feeds back the data to the crew. The computer continuously evaluates data from the different components and uses the redundancy of information as a technique for isolating equipment failures, which are identified with built-in test equipment lights. If the system is improperly modeled, if there are errors in the computer software, or if there are hardware failures in the test computer and equipment, the fault isolation function may fail. Consequently, although on-board equipment may have replaced the need for flight-line personnel who specialize in troubleshooting, a new class of highly trained technicians may be required who understand and can analyze the entire avionics system in cases where failures in the test equipment occur frequently.*

Requirements for Technician Skills

Test equipment available in the shop has become much more sophisticated in recent systems. Instead of oscilloscopes and voltage meters, the technician has available electronic test and diagnostic equipment--known as aerospace ground equipment (AGE). In many cases the technician plugs the component into the AGE and calls the appropriate computer program. The computer controls the test equipment throughout a test cycle which may last several hours, analyzes the data, and indicates which components must be replaced. Although the average level of skill required by the repairmen may have declined as a result of the proliferation of AGE of different types, many of the maintenance positions have

* In the case of the Mark II avionics on the F-111D, the manufacturer of the avionics has established a mini-depot at the wing to provide such expertise. For one troublesome mobile ground control approach unit, the Air Force established a team of officers, composed of electrical engineers, who studied interface problems in the system and established guidelines for the continuous monitoring and tuning required to keep the system operational.

become so highly specialized that there is little carryover from one test station to another. In addition to the other changes in electronics maintenance brought about by recent changes in AGE, maintenance of the AGE itself has become increasingly important. Such maintenance is estimated to be 10 percent of avionics maintenance costs for the A-7D and is perhaps as high or higher on other systems.

Some Manpower Considerations

The change in the electronics environment naturally raises a number of issues about electronics training and the manning of avionics maintenance squadrons and other units. These issues relate to the suitability of traditional electronics training, the proper skill mix when some of the maintenance functions have been greatly simplified, and the desirability of more detailed occupational identifiers, since test stations have become so highly specialized.

The problems in the new electronics are not exclusively manpower and training problems. Isolation of faulty equipment has become a much more complex task in recent systems. On many of the newer systems a given fault indication may reflect a failure of the specified equipment, but it may also indicate failure of a related piece of equipment or a software defect in the built-in test equipment. Maintenance personnel, of course, have no way of determining which is the case. Furthermore, there is no opportunity for the equipment operator to convey usable information to the maintenance personnel. As a result, in some cases retest OK rates have been as high as 80 percent at the unit and 35 percent at the depot. These maintenance problems are in part a symptom of another problem. Each avionics system is unique, and although each is highly modular, there is little interchangeability among components in different avionics systems.

ORGANIZATION AND OVERVIEW

As stated previously, the purpose of this report is to make recommendations which can reduce electronics maintenance costs in the DoD. The report is limited to manpower and personnel aspects of electronics maintenance, although because of the pervasiveness of manpower issues

in the maintenance field, we discuss weapons procurement and other topics which superficially appear to be non-manpower-related aspects of the problem.* This short-term study has tried to develop several types of recommendations: experiments and demonstrations that can be conducted in the short-run, actions or policy changes by DoD and the services that can be taken on the basis of what is now known, requirements and a rationale for studies or research to eliminate areas of uncertainty or to explore new approaches, and, finally, actions which should be taken to provide institutional support in the DoD and the services for other recommendations.

Section II is the body of the report and is organized into four main subsections: (1) a conceptual framework that relates each of the subject areas to the overall military system; (2) maintenance manning, which contains military manpower requirements and the substitution possibilities between the various categories of manpower; (3) job performance aids; and (4) the personnel and training system, which affects the training and capabilities of military personnel filling electronics maintenance billets. Recommendations contained in each of these subject areas are drawn together in Sec. III. The purpose of the Conclusions section is to summarize and provide a perspective for the recommendations dealt with in the specific subject areas.

* We do not, however, attempt to provide specific recommendations in peripheral areas.

II. RECOMMENDATIONS FOR LOWERING THE COSTS OF ELECTRONICS MAINTENANCE

FRAMEWORK FOR RECOMMENDATIONS

As we have noted, ARPA's tasks are to make recommendations that could, in the short run, offer potential reductions in electronics maintenance costs and could, in the long run, lead to research programs likely to reduce personnel-related electronics maintenance costs. However, one cannot completely isolate these maintenance problems from the larger system that produces our national defense capability. To help recognize interdependencies within various parts of the system, this section presents a more general analytic framework. This will enable a sharper focus to be brought on the task of recommending actions that could lead to reductions in manpower costs. At the same time, indirect ways to achieve maintenance savings may be pointed out, and potential failures caused by short-sighted recommendations (i.e., those that consider only the present status of electronics maintenance) may be avoided.

From a broad perspective we can see that the DoD objective is to produce desired levels of national defense in the most efficient manner possible. By efficient we mean that various missions should be performed efficiently in a technological sense *and* at minimum cost over the lives of the missions. This is a crucial point with respect to maintenance costs. It must be remembered that the maintenance labor required for carrying out various missions depends on the various requirements for these missions in the provision of national defense. Given a desired level of capability, certain amounts of combat labor and combat capital are needed and the amount of maintenance labor and the level of maintenance costs are really derived from the overall mission requirements and the types of capital used to carry out the mission.

There are three decisions that must be made almost simultaneously to ensure efficiency in the provision of national defense at minimum cost:

1. What quantities and types of weapons systems should be procured?

2. At what level of capability should these systems be maintained?
3. How should the level of maintenance be provided?

Figure 1 presents a highly simplistic view of the relationships that determine the level of maintenance demanded by operational considerations and the organization of maintenance activities. We will discuss in detail the relevant portions of this framework in later sections, but a brief overview touching on *all* aspects of the maintenance question is called for here. Future requirements for national defense result in the procurement of weapons systems (operational capital). As these weapons systems are introduced into the force, the performance of missions leads to equipment malfunctions. The repair of these malfunctions is carried out by a combination of maintenance labor, maintenance capital, and maintenance aids. Effective maintenance capital includes spare parts, tools, and various items of diagnostic equipment. This equipment may itself malfunction and so must also feed into the repair cycle. Effective maintenance labor interfaced with technical aids is produced by enhancing an individual's natural ability with formal training and on-the-job training. Thus, technical aids may enhance on-the-job training either directly or indirectly in the process of malfunction repair.

We have focused on manpower requirements, personnel and training, and technical aids--areas where changes could result in significant cost reductions for electronics maintenance. Figure 1 indicates the broad relations among the various areas but certainly does not portray the intricate interdependencies. Consider, for example, the procurement process. Weapons systems today incorporate many diagnostic aids that change the character of maintenance. The problem of troubleshooting becomes one of deciding whether a subsystem or a diagnostic aid has malfunctioned. This has great impact on formal training and on-the-job training. The system supplier prepares the technical orders and these determine what sort of interface exists between the maintenance man and the weapons system. Moreover, the factors discussed above simultaneously interact to set manpower requirements in terms of skill levels. If we

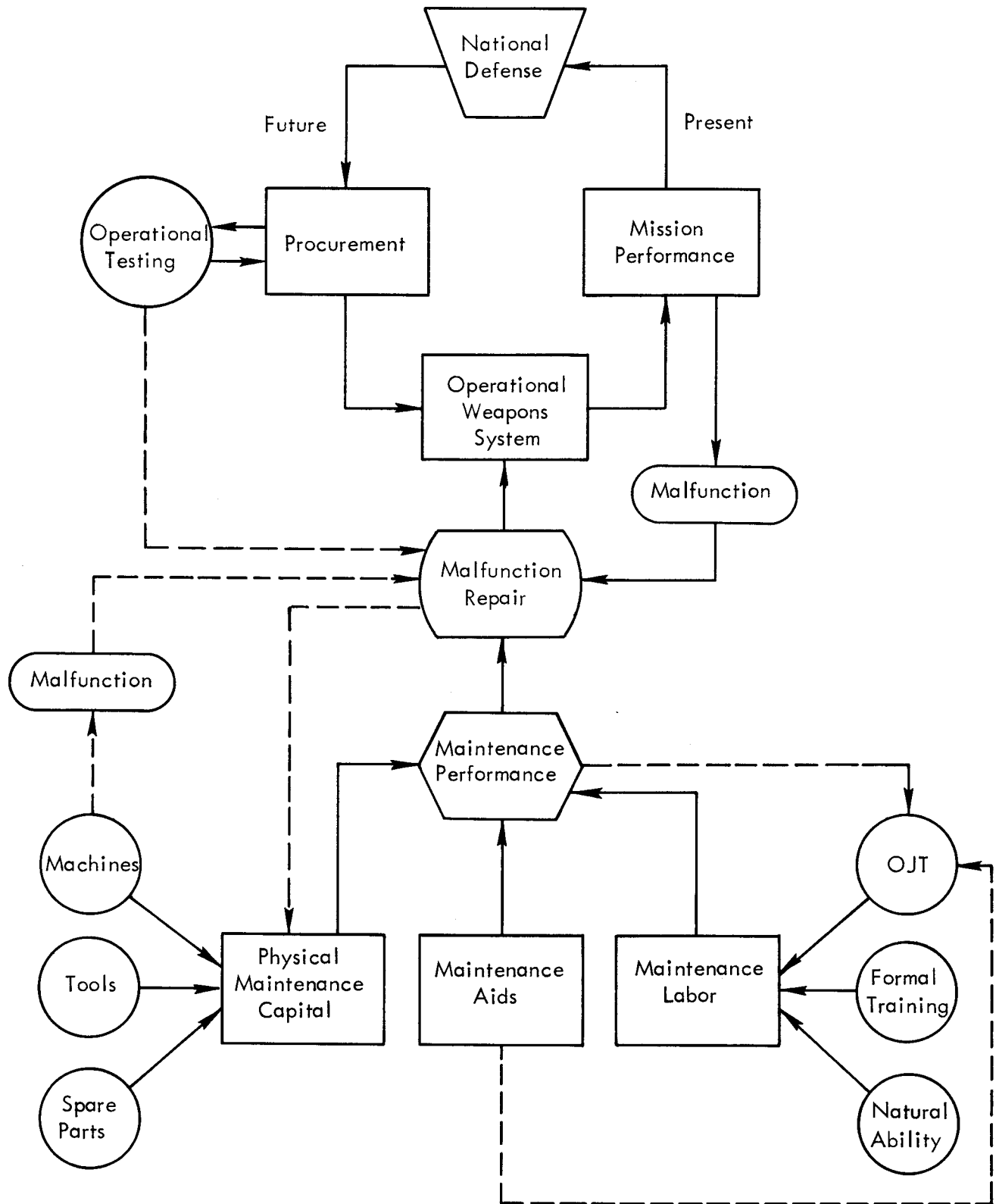


Fig.1 — The maintenance system

reverse the flow of thought, however, it is apparent that there are other implications. For instance, the development of maintenance aids as the system is built may uncover previously unknown maintenance faults which could be easily corrected prior to procurement of the system. It is clear that we should not approach the problem just from the electronics maintenance side but rather should consider changes in other parts of the system.

Our approach is to treat all factors as potentially variable to help reach our objective--finding the combination of factors that produces operational capability at minimum cost. If we divide these factors into two categories, capital (non-human resources) and labor (human resources) we find, as we have shown above, the large and increasing manpower costs of maintenance. As we have moved to the all volunteer force, we have seen the cost of manpower rising rapidly and faster than capital costs.*

As the cost of labor goes up relative to the cost of capital, to produce a desired level of capability we should first look to the substitution of capital equipment for labor. The question we then must ask is, How easy is it to substitute capital for labor in producing a desired level of national defense?

The most obvious method of substituting capital for labor is by way of the procurement process. This suggests that manpower planners should be as involved in the procurement process as the hardware planners. However, this can only incrementally effect savings in the sense that new procurement accounts for roughly 10 to 15 percent of the change in the capital stock. It would take many years to effect an overall change in the amount of capital employed in producing national defense relative to the amount of labor employed. However, this is one way of attempting to achieve what are in effect the cost savings--looking for opportunities to substitute capital for labor within new investment. This argues for increasing emphasis on the total life-cycle cost approach to systems acquisition, and it especially argues for emphasis on the maintenance

* Costs are defined as the unit cost of labor and the unit cost of capital. For evidence that the cost of labor has recently risen relative to the cost of capital see Ref. 6.

labor component within the acquisition process. This would seem to be one of the chief R&D strategies that should be employed to reduce electronics maintenance costs, since we are not only concerned with electronics maintenance costs *per se* but overall systems costs. We are not simply arguing for dollar costing of maintenance expenditures or new systems but rather for a conceptual change in procurement by explicitly considering alternative maintenance schemes for the same system.* Moreover, much work needs to be done on predicting the future course of military labor costs and labor productivity.

The future, however, is uncertain. Suppose in the next 10 years, after we have made an adjustment to a more capital-intensive force, the cost of labor begins to fall relative to the cost of capital. We would have to go through a reverse process, substituting labor for capital within the force. Such maneuvering is obviously not an appropriate response. The lags in the system would make adjustment costly in terms of time. This, perhaps, suggests that an R&D strategy with a large payoff would be to seek ways of increasing the ease with which labor is substituted for capital within the existing inventory of capital equipment and the labor force. In this way responses to changing relative costs could be quite rapid. From the point of view of uniformed personnel, flexible terms of service or even lateral entry might be sufficient to give flexibility to the labor component of the force. Civilianization--that is, hiring civilians for non-tenure positions--might be justified. On the other hand, in terms of capital procurement, it seems that the most effective way of ensuring flexibility is to attempt to purchase systems that do not require fixed amounts of labor.† The easier we make it to substitute capital for labor, or labor for

* A documented framework for detailed life-cycle costing may be found in Refs. 7 and 8.

† An example of increased flexibility would be the procurement and maintenance of "black-box" modules. If labor costs are very high and we wish to adopt a policy of performing maintenance simply by removing faulty "black boxes" and throwing them away, we would still want to ensure that these "black boxes" are repairable so that a switch to a repair policy would be feasible.

capital, within the force, the easier it will be to minimize the cost of producing a given level of defense output.

If the choice of a particular electronics system determines, within some range, the amount of labor required (and the methods required) to maintain it, then in the long run, the development and procurement of alternative systems will be the primary way of reducing maintenance costs. Based on past studies of airframes (including missile airframes), turbine engines, and some electronic systems, certain observations can be made which relate operations and maintenance (O&M) costs to the conduct of development and procurement programs.*

1. Most current concern during development is with predicting O&M costs, not lowering them.
2. Relaxing performance requirements would reduce O&M costs.
3. A pause between the development and production of an article could be used to verify performance and maintenance costs and to develop associated maintenance aids and techniques.

There are two apparent paths toward improved reliability and maintenance experience for new electronics systems. One of these is through relaxation of the performance requirement. By relaxing performance requirements, the designer is often able to use better-known design techniques and is able to incorporate standardized components or subsystems specifically designed for low maintenance. This approach might actually reduce the cost of the development phase and also reduce O&M costs.†

The other basic approach requires increasing the development phase duration. Because we do not have the techniques to predict accurately the reliability or maintenance cost of a new system or component while it is still being designed, our only recourse is to test the item

* We have provided a selected bibliography of such studies at the end of this report.

† Some individuals argue that the last 10 percent of performance takes 50 percent of the development money.

thoroughly before production, redesign it as needed, and then retest it before large-scale production.*

Inserting a "pause" between the development of initial test items and the initiation of quantity production so that tests can be conducted and their results can be reflected in design changes creates a problem in that a great many incentives exist to move into production as soon as possible, even before operational performance and maintenance costs have been verified. Every development and acquisition program should be viewed as a source selection competition and in a general way one should ask, "Can we develop a Y to replace X?," rather than claiming from its inception that "Y is being developed to replace X." By viewing a development and acquisition program as a *search* for options, competition of a sort is created and, if properly managed, is maintained throughout the program--for example, by comparison of an advanced system with a product-improvement version of an existing system, of two or more systems from a parallel development strategy, or of a product-improvement system with the current one.

Since within this philosophy development programs are searches for options, it seems wise to conduct them in an "austere" manner. The design-to-cost development and procurement strategy is an important move in the right direction, but its application may be restricted to acquisitions where the expected technological advance is modest. Our hypothesis is that for many acquisitions the uncertainties in the cost-schedule-performance relationship are too great to permit a satisfactory *predevelopment* decision as to a suitable unit procurement price. An interesting acquisition strategy applicable to systems requiring more than modest advances in technology is the prescribed-price development program followed, perhaps, by a general competitive bidding for a fixed-price production contract. By introducing as few specifications as possible, perhaps citing only what the system is needed for, greater opportunities should be provided for contractors to innovate and to

* Warranties might have the effect of forcing developers to do this themselves. There is the danger, however, that the developers might simply attempt to extract high prices for incurring the risk of such warranties for untested items.

exploit engineering tradeoffs arising during development in the direction of reduced O&M costs.

Taking the implications of the results of the more general studies and applying them to maintenance, one can conceive of certain possibilities for reducing maintenance costs. The inclusion of maintenance and the development of maintenance aids within the initial design phase would emphasize maintenance costs and, perhaps, isolate faulty maintenance designs. During the operational testing phase of new weapons systems, maintenance specifications could be made one of the prime criteria for accepting or rejecting a system. The analysis of maintainability during operational testing is almost an evolutionary type of experiment in that the validation of technical aids may lead to substantial improvements in maintenance requirements.

If we are to attempt to carry out some of these suggestions, we must immediately turn to the institutional relationships that determine how the system reacts to changing relative costs. It should be noted that the method of budget submission required by Congress results in an asymmetric treatment of capital and labor services. The reaction to changing relative costs will be obscure when one looks at the total cost rather than the annual cost of a weapon. One does not look at the total cost of uniformed personnel but instead at the average annual cost. The budget should be structured in terms of the annual cost of labor and the annual cost of capital. Furthermore, the method for determining manpower utilization in the military also tends to promote slow responses. In each of the services and in the OSD, separate organizational entities are responsible for determining manpower requirements and for fulfilling those requirements. The demand for manpower therefore tends to be constructed independently of personnel requirements. Only when individual requirements for manpower and capital are aggregated into total service budgets is there a general concern for costs. This lack of visibility at the lower planning echelon results in the types of gross adjustments that cut force structure rather than re-allocate resources within the given force structure. Obviously, these institutions must be changed to make sure that when methods of cost savings are found, these changes are, in fact, carried out.

In our previous discussions we have been talking in the abstract about the substitution of capital for labor, or the substitution of labor for capital. It should be noted that capital and labor are generic terms that include all of the possibilities that we will explore below. Job performance aids have been suggested as one of the prime ways of reducing maintenance costs. One needs less-skilled maintenance personnel to carry out tasks and perhaps fewer of them. It institutionalizes on-the-job training and makes people more effective. But, JPAs are capital; they include books and other materials that are an investment in the production of maintenance activity. Our task in seeking methods for ensuring economic efficiency is to focus on a careful separation of technological possibilities so that the least costly process is used to produce our desired level of national defense.

One of the most important problems to be faced in producing national defense is the measurement of labor productivity. This affects both current and future evaluations of recommendations for changes in the maintenance structure. As we conceive of substitutions of one input for another to enhance labor productivity, we must be able to make appropriate judgments on how to make operational tests of such substitutions. The ability to make such tests would have great impacts on our perception of substitution possibilities and would thus affect the procurement process, manpower requirements, and technical aids.

MAINTENANCE MANNING POLICIES

In attempting to reduce the personnel costs of maintaining electronics systems, manning policies assume central importance. Policy changes in procurement, maintenance strategy, maintenance aids, training, etc., all must be accompanied by appropriate changes in manning policies if they are to result in maintenance cost savings. For example, it was previously noted that procurement of equipment that permits variations in the capital-labor mix in maintenance is valuable only if it can be accompanied by flexibility in maintenance manning; introducing JPAs that raise labor productivity reduce costs only if accompanied by reductions in manning. More important, reevaluation of manning policies themselves, aside from changes in other aspects of maintenance policies, may result in sizable savings.

The term "military manning policies" is used here to refer to the set of interrelated issues that involve determination of the amount of manpower devoted to provision of military maintenance services. These issues include determination of the number of manpower billets for a maintenance unit, the mix of skill levels in the unit, the level at which the maintenance activity takes place (e.g., intermediate versus depot), and the types of labor services to be used (military, civil service, or contractor). With a given capital stock, numerous manning policies can be adopted which will produce a given level of output; however, some will be more efficient than others--that is, less costly for a given level of military capability. The purpose of this subsection is to describe some of the considerations that are relevant in selecting among alternative manning policies and to suggest research that would be valuable in providing the types of information needed to select efficient policies. There are, of course, a number of problems in this area which are unique to electronics maintenance. However, with respect to the topics considered here, the differences between electronics maintenance and other types of maintenance may not be as important as the similarities.

One feature which is common across services and types of maintenance is that effective maintenance management is limited by the lack of adequate measures of cost and productivity. It is necessary to have data on maintenance costs at each level (organizational, intermediate, depot). Three types of performance measures are needed: (1) measures to reflect operational capability, (2) measures of maintenance quality (mean times between failures, mean times to repair, retest OK rates, etc.), and (3) measures of individual productivity, particularly estimates of productivity for apprentice-level personnel, which can be used to estimate on-the-job training costs. Although many of these measures exist in one form or another, the data are characteristically so incomplete and inaccurate as to seriously limit their usefulness as a tool for analysis. Data can be collected by test and evaluation teams sent to the field but such efforts are likely to be extremely costly. Therefore, the most desirable method of assembling the necessary data would be to use existing reporting systems for collecting cost and operational

data, and to supplement this information with a sampling of other data collected in the field.

Of the three types of data cited above (cost, unit performance, individual productivity), cost data are the most easily attainable and the most reliable. The military services, particularly the Air Force, have taken steps to develop cost reporting systems that attempt to collect all of the costs related to maintaining particular systems. The Air Force's IROS cost system accounts for both the number of maintenance man-hours devoted to a particular system at the organizational and intermediate levels and the number of man-hours at the depot devoted to the same system. The cost of replacement units is also estimated and accounted for. Such a system provides useful service-wide data for particular systems but does not permit the evaluation of a single operational unit. To determine maintenance costs for a particular unit, one can identify time charges and parts consumption at the unit level by using such reports as the Air Force form 66-1, but even these data do not provide a full picture of maintenance costs.

Despite the difficulties cited above cost data are far more reliable than data currently available to measure unit performance or the productivity of individuals. The chief problem in measuring unit performance is likely to be conceptual rather than data-oriented. Operational readiness rates are probably available in most cases (the Air Force report 65-110 includes such statistics), and maintenance statistics can be collected at the unit level, but apparently little effort has been made to apply these data in estimating efficiency in maintenance or other activities. What is needed are models of the maintenance activity and its relationship to mission achievement. This subject is discussed more fully below in relation to manpower requirements.

Data on individual productivity, particularly for apprentice-level personnel, are necessary to evaluate the impact of such innovations as JPAs on the costs of on-the-job training. Estimates of the productivity of newly trained personnel have relied primarily on detailed supervisory evaluations of individual enlisted personnel* or on the time required

* See Ref. 9. The methodology and plans for future research are discussed in Ref. 10.

for skill upgrading. A disadvantage of the latter measure is that skill upgrading tends to be an institutionalized event not necessarily closely related to the individual's progress on the job. Also, the written test administered to a candidate journeyman may bear little relation to the individual's capabilities and performance on the job. Properly conducted supervisory evaluations are a valuable and inexpensive method of estimating productivity; in addition, performance testing* and peer ratings may be desirable methods of estimating progress on the job.

Performance testing of personnel with various amounts of experience permits identification of the areas in which a newly trained individual differs from one with six months or one year of experience, etc. Performance testing on a routine or recurring basis should also provide valuable feedback to the training commands--perhaps by identifying areas where training is deficient but certainly by providing a method of evaluating changes in training. The principal barrier to widespread performance testing is undoubtedly the cost. One alternative which might be considered is selective augmentation of existing data systems at regular intervals to include desired information on individual productivity. However, the data are so important to effective decision-making that even if data collection is quite costly, it is probably desirable.

Recommendation 1: Continual and systematic performance testing of random samples of enlisted men should be undertaken, to provide a basis for estimating productivity and the factors influencing it. This should begin with the largest electronics career fields because potential savings are greatest there and because large samples increase the reliability of statistical estimates. The following career fields should be included: Army, Tactical Electronic Equipment Maintenance (EE) and Air Defense (AD); Navy, Electronics Technician (ET) and Aviation Electronics Technician (AT); Marines, Avionics (62); Air Force, Communications Electronics Support (30) and Avionics Support (32).

* Performance testing involves rating a technician's work as he performs specified tasks in his specialty.

Manpower Requirements

As has been previously noted, setting standards for manning military units (manpower requirements) is crucial in reducing the costs of electronics maintenance. In this subsection only issues related to manning operational units are considered; issues relating to the division of maintenance between operating units and depots and to the method of contracting for depot personnel are discussed in the next subsection.

Because so much money is spent annually to hire maintenance personnel, the potential savings from having fewer personnel are large. Our rough estimate of the annual cost of military electronics maintenance personnel is \$3 billion; this implies that a 10 percent reduction in manpower would reduce costs by \$300 million annually. Of course, a 10 percent reduction in manpower might require increased expenditures of other types to retain the same level of capability, but in view of the difficulties in establishing appropriate manning levels, one cannot be sure that this would happen. Moreover, reductions in manning are necessary if the potential cost savings from JPAs or if other increases in capital goods are to be realized; otherwise the result will be either increased output or increased leisure time for maintenance personnel.

Setting manning standards is difficult because so many factors influence a maintenance group's productivity, including the experience and proficiency of group members, their experience working together, the prevailing maintenance policy (e.g., acceptable operational ready rates), rates of usage, failure rates of equipment, and the division of work among levels of maintenance. Current manning policies allow for some of these factors but assume that other factors do not vary across installations or are subject only to small random variations. Although the skill mix affects the manning standards for a unit, it is often not accounted for in actual manning practices. Similarly, rules governing differences in maintenance demand are often not sufficiently sophisticated to reflect real-world complexities. In such cases some reassignment of manpower would increase total military capability. Maintenance policies which are taken as given, such as the distribution of repair tasks between operational unit and depot or acceptable operational ready rates, may be selected inappropriately. Finally, factors

which are assumed to average out, such as experience in working as a group or equipment failure rates, often do not. Further complication of the problem results because very little evidence exists on the relative importance of (or interrelationships among) the factors influencing manning standards.

What is needed is a model or set of models that can predict the relationships between different mixes of inputs and a maintenance group's productivity. Computer simulation models of the operations of a military unit are potentially valuable in this regard. Several such models exist for simulation of Air Force operations,^{*} and similar models may exist or could be developed for the other services. An advantage of this approach is that it is much less costly and time consuming than experimentation--a matter of some importance in view of the large number of factors that influence desirable manning levels.[†] Such models should relate maintenance labor inputs and other inputs to measures of military output, so that they can provide a basis for estimating and valuing labor productivity. Marginal labor productivity can be estimated by simulating the effect of small changes in labor input on output and can be valued by finding the least costly combination of other resources that will keep output constant in the face of a reduction in labor input.

If done effectively this would be a major undertaking but developing such models is justified in view of the complexity of the problems and the amount of the potential savings. These models should be designed so that alternative maintenance policies, such as varying the frequency of scheduled maintenance, can be evaluated. In using these models, the appropriate approach is to select the combination of inputs that yields the desired *wartime* capability at minimum cost. In all probability this will require special data-collection efforts, but it is crucial to setting efficient manning standards.

For the short term there are at least two potentially useful sets of data. The sortie rate analysis,⁽¹⁵⁾ which uses the SAMSOM model and

^{*}For a description of models developed at Rand, see Refs. 11-14.

[†]It should be noted, however, that data requirements for the type of model being considered here are substantial, and collection of required data (and validation of models) will require some experimentation.

experience from Southeast Asia and elsewhere for several types of aircraft, is one possible source. In addition, a test recently completed by TAC using F-4s and the logistics composite model may prove useful.* In that study, data on repair times were gathered in the field and were combined with other input data in a simulation of the activities of an F-4 unit with a specified flying program. Subsequently, a three-month controlled experiment was conducted at Seymour Johnson Air Force Base, North Carolina, in which an F-4 squadron was given the same flying program as a check on the accuracy of the simulation program.

Simulation models may also be useful in developing appropriate productivity weights for manpower with differing amounts of experience. The existence of reliable weights would provide a basis for investigating the possibilities for using a single, aggregated figure (which represents manpower weighted by estimated productivity) for manpower authorizations and assignments. This would be desirable for at least two reasons. First, because of data limitations, the present methods of determining the authorized skill level or pay grade distribution for each unit leave something to be desired. Second, actual assignment practices often diverge significantly from authorizations--especially with respect to the experience mix.

Recommendation 2: Research should be undertaken to develop models of military units (where appropriate), to validate the models, and to apply them to the evaluation of manning standards. The possibility of determining manning standards based on data and programs already in existence should be seriously considered. Research should be conducted using simulation models and other methods to develop productivity weights for personnel with differing amounts of experience.

One problem in determining manning standards is that there is very limited information on how different maintenance policies affect the depreciation rates of equipment. Some currently available data can be brought to bear on this issue, however. Military aircraft in Southeast Asia received much less maintenance than similar aircraft in the CONUS.

* This study, conducted through the Office of the Deputy Chief of Staff, Plans, Headquarters, Tactical Air Command, was completed in June 1973 but has not yet been published.

Comparisons of current failure rates and repair costs across aircraft of similar age but with different histories of usage could be used as a measure of the cost of reduced maintenance. Also, since commercial airline maintenance policies differ from military policies, similar comparisons could be made between aircraft in military and commercial use. Because military and civilian aircraft use may differ radically, it may not be possible to compare costs for the entire aircraft. Nevertheless, military and civilian aircraft will occasionally have identical electronic subsystems (for example, the Carrousel inertial navigation system), which provides an unusual opportunity to compare maintenance practices and problems. Differences in repair equipment, manpower proficiency, flying programs, etc., may preclude statistical analysis of differences in observed performance, but qualitative information on where differences exist and what their magnitudes are could provide valuable insights.

Recommendation 3: Efforts should be made to identify electronics subsystems used by both the military and commercial carriers and to make comparisons of maintenance practices and costs. In particular, DoD should study the Carrousel inertial navigation system developed by General Electric.

Other Aspects of Manning Policy

In the preceding discussion only organic maintenance (i.e., maintenance conducted at the operating military unit) was considered. The relationship between organic and depot-level maintenance was taken as given, and it was assumed that organic maintenance would be performed by military personnel. In this subsection the use of contractor personnel in military maintenance and the substitution of depot maintenance for organic maintenance are considered.

A recent study by Thomas Rowan, which was conducted as part of the Electronics X study and which is the main basis for the recommendations on electronics maintenance and support made by the Defense Science Board Task Force on Electronics Management,⁽³⁾ suggests that wherever possible military maintenance should be provided by civilian contractors. This can be done in two ways. Contractor personnel can be hired directly,

primarily for depot repair. The alternative, which may not appear equivalent to the hiring of contractor maintenance, is to purchase failure-free warranties at the time of equipment procurement (an increasingly common practice with commercial airlines). Contractor-provided maintenance may in fact be cheaper than present arrangements, but there is currently very little evidence on this issue. Moreover, cost comparisons must be very carefully done, since what appear to be real cost differentials frequently are reflections of differences in accounting practices.

One way to explore the relative efficiency of contractor maintenance relates to initial procurement practices. When new electronics equipment is purchased, the contractor who produces it commonly provides depot-type repair services for a time before military depots are established. This is true of the Mark II avionics on the F-111D, for example, where contractors have essentially established a mini-depot at Cannon Air Force Base, New Mexico.

Recommendation 4: Data on the costs of contractor depot repair during the early stages of equipment acquisition of recently developed electronics systems should be compared with regular military depot repair costs where possible. The N-16 and Kearfott-Singer ASN-90 inertial navigators are two systems that might be compared.

The criterion of unit self-sufficiency precludes the use of contractor personnel for most organic maintenance. However, some possibilities for using contractors in this way do exist and are being exploited. For example, the Air Force is using contractor personnel almost exclusively on one of its nine bases where undergraduate pilot training is given (Vance Air Force Base, Oklahoma). This arrangement provides an excellent opportunity to explore not only the magnitude of cost differences but the reasons for them.

Unit self-sufficiency does not necessarily require unit repair capability for all equipment. For example, the Air Force has recently adopted a policy of eliminating all field repair of the LN-12 inertial navigator on the F-4, although base-level testing and calibration of equipment that seems faulty is still done. Also, the Navy does not

attempt shipboard repair of submarine precision gear trains. Case-by-case analysis of electronics systems would probably reveal many instances where organic repair capability could efficiently be eliminated.* One reason that organic repair is almost universal is that present maintenance decision criteria tend to indicate that it is efficient in almost all instances. This is partly because for purposes of analysis it is assumed that where both field and repair capability exist, they provide diagnostic and repair capability of equal quality. Both of these assumptions are questionable. For example, limited data in one recent unpublished study showed that average operating time before removal was 22.7 hours for FB-111 inertial navigators repaired in the field and 34.0 hours for units repaired at the depot.†

Recommendation 5: Comparisons should be made, where possible, of field and depot retest OK rates and failure rates after repair. These should be used to evaluate the relative diagnostic and repair capabilities at the base and depot levels. The integrated display on the F-111D and the inertial measurement set on the A-7D are candidates for study.

JOB PERFORMANCE AIDS

Much of the research concerned with maintenance personnel has been devoted either to training or to maintenance aids. Maintenance aids as we use the term here includes information stored either in devices or in documents, available at the job site to assist the technician in performing his tasks. An example of such a maintenance aid would be the well-known technical order. JPAs are a large subset of maintenance aids and most research on maintenance aids has focused on JPAs. JPAs are distinguished from other forms of maintenance aids in that they attempt to

*The absence of organic repair for a system does not, however, imply the absence of organic maintenance. Personnel would still be required in the units to remove, test, adjust, and replace equipment. However, eliminating organic repair capability would reduce both the number of personnel and the average proficiency required in the unit.

†Personal communication from D. W. McIver, The Rand Corporation, August 1973.

lay out in logical progression the tasks that should be performed in a given job. A JPA does not have any particular form or particular level of detail; it may be a fully proceduralized aid, which provides step-by-step directions, or it may provide a logical picture of the system, thereby assisting the technician in deciding what steps to take. A distinction is almost always made between aids for troubleshooting and aids for nontroubleshooting tasks. JPAs developed for nontroubleshooting tasks (routine or "straight-line" maintenance) have invariably been fully proceduralized aids, providing an ordered, comprehensive set of instructions for performing each task. While fully proceduralized troubleshooting aids have been developed, most of the research on troubleshooting has involved decision aids to help the technician formulate a strategy for isolating faults. A common example is the maintenance dependency chart, a device that helps the technician understand the interrelationships of a complex electronics system.

JPAs are potentially beneficial in three ways: they could (1) reduce troubleshooting time and the costs associated with faulty troubleshooting (such as reduction in readiness rates, costly retest OKs, and unnecessary consumption of spares), (2) reduce on-the-job training for trainees and for journeymen-level personnel assigned to new equipment, and (3) as the proponents of JPAs strongly believe, reduce the amount of training required for electronics maintenance personnel. As evidence of the effects of JPAs, one can cite approximately 20 studies performed over the past two decades. These have been summarized and discussed by Rowan⁽¹⁶⁾ and are listed in the Bibliography. While no single study or experiment is convincing by itself, the totality of the evidence represented by these studies provides solid support for the JPA concept. In some of the cases reported, faster repairs or fewer errors were made by the group using well-designed aids. In other cases, equivalent performance was obtained where the test group was less experienced, had lower aptitudes, or had received substantially less training than the control (or non-JPA) group. In some cases, the results reported border on the spectacular. In one study involving FPTAs, high-school students given 12 hours of training reputedly performed at a level comparable with the control group, which consisted of Air Force technicians with from five to seven years of experience in the field.⁽¹⁷⁾

The potentially large savings to DoD from reduced formal training or from reductions in the cost of on-the-job training or cross-training can be measured within a framework which includes the cost of formal training, the cost of on-the-job training, and the return to the military from these investments in training. Figure 2 shows these costs for a hypothetical individual after he completes basic training. Formal training costs have two components--the pay and allowances of the trainee plus the direct outlays on training (for instructors, materials, equipment, etc.). After formal training, the individual acquires additional skills and becomes more proficient. This represents on-the-job training. On-the-job training is also required in electronics to make trainees familiar with the specific equipment to be repaired. In estimating the costs of on-the-job training and the returns to training, it is necessary to compare the cost of pay and allowances with the estimated value of the individual's net productivity over time. The productivity curve may be negative initially, reflecting the fact that supervisory costs may be greater than the individual's contribution to his unit. As soon as productivity exceeds pay and allowances the military service begins to earn a return on its investment in technical school and on-the-job training.

On-the-job training costs can be sizable compared with formal training costs. In one Air Force specialty--flight maintenance specialists (AFSC 431x1)--these costs were estimated as \$6600 and technical school costs for the 12-week course were only \$3200 per man.⁽⁹⁾ In the electronics area, formal training courses are on the order of 30 weeks, and formal training costs typically exceed \$10,000 per graduate. Few estimates have been made concerning the costs of on-the-job training for maintenance personnel. Weiher and Horowitz⁽¹⁸⁾ have estimated the total costs of first-term training for Navy aviation electronics technicians and electronics technicians. For those attending formal school the average cost of *both* school and on-the-job training was \$9572 per electronics technician and \$14,444 per aviation electronics technician. For those receiving *only* on-the-job training and no formal schooling the average cost was estimated at \$14,461 per electronics technician and \$19,461 per aviation electronics technician. While these estimates may vary somewhat

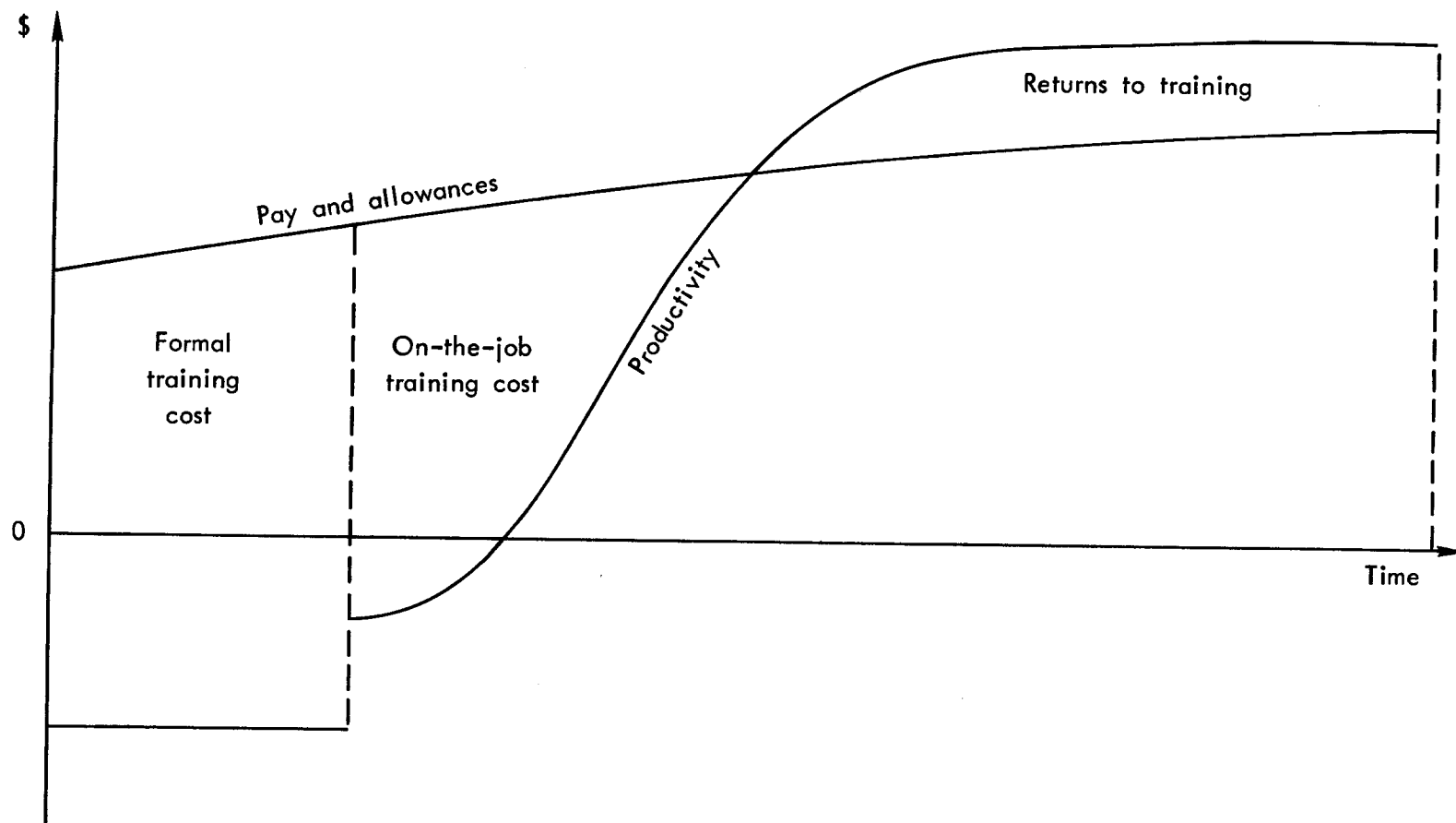


Fig. 2 — Cost and returns to military training in the first term of service

with respect to true costs, nevertheless, they are considerable. If JPAs can drastically reduce training time and can make individuals fully productive almost immediately, the potential savings per trainee may be as high as \$10,000. For DoD, where approximately 40,000 men are trained annually in the electronics maintenance area, the total potential savings may be as high as \$400 million per year,* if JPAs can match the claims of their strongest advocates.

Of course, the introduction of JPAs does not automatically result in the realization of savings approaching this magnitude. Actual savings would result from actions like reducing training and reducing manning levels for units manned by more proficient personnel, not merely by the introduction of JPAs. To achieve these changes, it is necessary to be able to evaluate the productivity of individuals and units and the effect that JPAs have on this productivity. This is the essence of the recommendations in the previous subsection. The remainder of this subsection is organized into five areas in which recommendations are made with respect to JPAs. First, recommendations are made for actions that can be taken in the short run to evaluate the effects of JPAs. Since there are major unresolved research issues dealing with JPAs, especially those for troubleshooting, we also discuss actions that can be taken on the basis of existing knowledge and areas in which further research is required. Problems collateral to the introduction of JPAs are identified: the economics of production of JPAs, the training required to support their introduction, and their implications for the procurement process.

JPAs in an Operational Context

Although much experimentation has been done with JPAs, there has been almost no experience with the introduction of aids into an operational setting. Therefore, experimental results with JPAs must remain partially suspect until they are confirmed in the field. First, experimental data, such as mean times to repair, or successful repair rates, are difficult to translate into maintenance costs, but more important,

* One must recognize, however, that other inputs, namely JPAs, are being substituted for training and that the substitution involves some increases in the expenditures on JPAs.

the controlled conditions under the experimental mode may be so radically different from actual practices in the field that laboratory results may not have much meaning. Thus, to really judge the value of job aids, it is necessary to monitor and evaluate the impact of JPAs employed in actual operations.

Moreover, introduction of JPAs will effect savings by reducing manpower required for maintenance and by reducing training. To establish that such changes would lead to more efficient maintenance, estimates must be made of both maintenance costs and operational capability resulting from maintenance actions. If JPAs in combination with either reduced manning or reduced training lead to more efficient maintenance, then obviously the same operational capability can be achieved at lower costs.* In this regard, all of the recommendations of the previous subsection apply: There is a strong need to develop the capability of measuring productivity and performance for both individuals and units. More important, if maintenance units or maintenance activities are generally overmanned in the military, then the benefit to DoD and the services from instituting JPAs will be zero or near zero. Even though JPAs may be highly effective on an individual basis, the introduction of JPAs would exacerbate whatever overmanning problem already exists.

During the next year DoD will have the opportunity to experience several types of JPAs, as discussed below, and in each case efforts should be made to monitor and evaluate their effects. One question that must be settled relates to experimental design--the problem of having comparable units operate with and without job aids for a particular system. This can be accomplished by assigning JPAs so that units chosen to receive them will be comparable to those that did not. Since it may be very difficult to get comparable units, a more realistic procedure is to compare a unit "before" and "after" the introduction of job aids. Phased introduction offers another benefit in that the service can identify faults in the JPAs or improvements in training techniques which will facilitate later phases of the innovation.[†] In all

* Or greater operational capability can be achieved at the same costs.

[†] See Ref. 19 for a brief discussion of the methods and problems of experimentation in personnel management.

experiments or demonstrations the actual operation of the unit must be observed to properly measure the impact of JPAs. Commanders may divert manpower resources away from the JPA system, not in an attempt to defeat the experiment (although such behavior is possible), but because the JPA is effective and his manpower resources are better utilized elsewhere.

Short-Term Demonstrations Involving JPAs

During the next year, DoD and the services can take steps to increase our limited knowledge of the effectiveness of JPAs in an operational context. In one case, as a result of the system of job aids being developed for the C-141A, an entire weapons system will undergo a changeover from conventional technical orders to JPAs. In two other cases, job aids for electronics subsystems are being developed and will be available for field tests in the coming year. Both of these new JPAs have been sponsored by the Navy for avionics systems (the AQA-7 sonar subsystem and AWG-10 fire-control system). Field tests have been planned for the AQA-7 job aids, but some questions about funding for the tests remain unanswered. Although AWG-10 job aids have been developed and tested with favorable results, the Navy is not providing funding which would permit completion of research in the integrated job aids for the fire-control system. The Navy is reportedly experiencing maintenance difficulties with the AWG-10, apparently because many senior personnel have been switched to the AWG-9 system. Because this may represent a troublesome area for the Navy and because improvement in maintenance can be measured, the completion of development of the JPA system and its introduction to operational use appear to have considerable merit.

The C-141A represents the most far-reaching opportunity to evaluate the JPA concept in actual operation. The development of these aids began with project PIMO (Presentation of Information for Maintenance and Operations), which was carried out by Serendipity Associates for the Air Force between 1964 and 1969. PIMO consists of fully proceduralized aids for non-troubleshooting tasks and other types of simplified aids for troubleshooting tasks. This system, according to Rowan,^{*} has

^{*}Reference 16, p. 52.

absorbed between 50 and 60 percent of the research funds devoted to JPAs. The PIMO system will be introduced into actual operation beginning in September 1974. Plans to monitor and to evaluate PIMO should begin almost immediately to ensure that accurate estimates of the impact of the JPA system will be forthcoming. These plans should cover three facets of the evaluation process: monitoring the new system, including assembly of data required and the use of field teams, collecting maintenance costs and the other data items to establish a "base line" prior to introduction of JPAs, and, finally, investigating the possibilities for phased introduction of JPAs in such a way that units comparable to those with JPAs may serve as a control group.

Recommendation 6: The introduction of the PIMO system of job aids for the C-141A should be monitored and evaluated to permit comparisons of maintenance costs and measures of productivity or maintenance efficiency with and without the JPA system. Planning and data collection for monitoring and evaluating the new system should begin immediately.

Recommendation 7: The development of job aids for the AQA-7 sonar subsystem should be followed up with field tests. The Navy should ensure that the field tests are properly conducted, using control groups, collecting data on maintenance costs and performance for the sonar subsystem and on mean times to repair, and collecting other statistics for individual technicians.

Recommendation 8: The decision to cease development of the integrated job aids for the AWG-10 should be reconsidered by the Navy. If resumed development is recommended, plans should be made to make the job aid system operational as soon as possible. Again, securing baseline data and creating proper control groups should accompany introduction of the system so that the valuable opportunity to evaluate these types of JPAs is not lost.

One problem with the development of JPAs has been the relatively small amount of resources devoted to research in this area. Rowan has estimated that only about \$5.0 million has been devoted by DoD and the services to the development of JPAs.⁽¹⁶⁾ Although many small research studies have been completed, they appear to have had little impact.

In view of the magnitude of the maintenance problem and the promise of JPAs as suggested by previous studies, there are strong arguments for a series of large-scale, well-planned, adequately funded field demonstrations of job aids.

The Air Force Human Resources Laboratory's Project Innovate proposed an effort which would have provided such a demonstration for one Air Force specialty code. The project, which was only partially funded, would have compared conventional technical orders, troubleshooting decision aids, and FPJPAs. It would have investigated the type of training and the degree of aptitude required for personnel using JPAs and the extent to which JPAs reduce cross-training problems. In addition to the lengthy training required in the electronics area, new trainees and technicians transferring to unfamiliar equipment must receive extensive on-the-job training before they can be effective. The purpose of the demonstration was to determine whether initial training with JPAs would facilitate the transfer of personnel to unfamiliar equipment. With limited funding AFHRL will not be able to examine the issues related to training, aptitude, and cross-training, but instead will concentrate on the development of JPAs for a single-equipment Air Force specialty.

Recommendation 9: In view of the importance of large-scale demonstration of JPAs and the long start-up time involved in such a demonstration, the Air Force should provide funding to expand the scope of the ongoing AFHRL study to compare alternative types of technical documentation.

Wholesale implementation of job aids for all types of tasks must await further research, particularly R&D on troubleshooting aids. (A list of topics for future research appears in the following subsection.) On the other hand, the technology for FPJPAs for straight-line or non-troubleshooting tasks has been developed sufficiently to permit their use for routine maintenance on electronics systems. Given the potential of job aids for reducing on-the-job training costs, DoD and the services will be undertaking little risk by having FPJPAs developed for all new systems to assist in the common tasks of checkout, adjustment, alignment,

and calibration. FPJPAs could be produced in conjunction with either conventional or improved technical orders, which would provide instructions for tasks not covered by the job aids and instructions for troubleshooting. The job aids should help reduce the time required for personnel to become oriented to a new electronics subsystem; furthermore, the tasks covered are performed as part of organizational or intermediate maintenance, where high turnover rates and the presence of inexperienced personnel may constitute more of a problem than at the depot.*

In principle, a JPA could contain any level of detail in the logical ordering of tasks. An important quality dimension among JPAs is the extent to which aids are based on a careful analysis of all the tasks a technician must perform in maintaining an item of equipment. The Air Force Systems Command has developed a specification, Mil-J-83302, which requires certain subproducts, such as a task inventory, that are meant to ensure the quality of the final product. AFHRL has recently developed a draft specification (TR 73-43) to replace the older mil spec developed by AFSC for the Vietnamization program.

Recommendation 10: Non-troubleshooting job guide manuals should be developed for all new equipment. They should cover the tasks of check-out, adjustment, alignment, and calibration and should be developed using the draft specification for FPJPAs in TR 73-43.

Fully proceduralized aids covering non-troubleshooting tasks may also be a desirable innovation for existing equipment with high maintenance costs. This may be true only if costs are due to calibration difficulties, for instance, rather than to poor fault-isolation ability or improperly designed hardware or software components. The latter problems have been characteristic of the more troublesome avionics systems introduced recently.

Recommendation 11: FPJPAs for non-troubleshooting tasks should be considered, especially for maintaining high-cost equipment now in the inventory. A review should be undertaken to determine if maintenance

* Depot maintenance is more commonly performed by civilian personnel, whereas organizational and intermediate maintenance tends to be performed by military technicians.

costs can be reduced significantly by improved performance of routine maintenance. (FPJPAs should be developed from the same specifications and for the same sets of tasks as listed in Recommendation 10.)

Research Requirements for Job Aids

As mentioned above, numerous unresolved issues remain concerning JPAs, particularly aids devoted to troubleshooting, which should be addressed in future research on job aids. If rapid progress is expected in settling the unresolved issues, support for JPA research should be increased from the recent average of less than \$1.0 million per year. Rowan recommends from \$4 to \$5 million per year funding for research, which does not seem unreasonable.⁽¹⁶⁾ Total annual expenditures on JPAs, if these are procured for all new electronics systems and subsystems, would of course far exceed the amount devoted to research.

The development of aids for troubleshooting is inherently far more difficult than the development of aids for routine maintenance. Decision aids suggest strategies for fault isolation and help the technician in a far more subtle way than fully proceduralized aids. Past comparisons, in fact, have shown maintenance dependency charts to be less effective than either conventional technical orders or fully proceduralized aids,* so further development is needed before this concept can be properly utilized. Fully proceduralized troubleshooting aids (FPTAs) are considerably more complex than either aids for routine maintenance or the decision aids for troubleshooting, since FPTAs must be able to lead the technician from the initial symptoms through a series of branching operations to isolate the fault. Among the difficulties with FPTAs is their sensitivity to human error, which may lead the technician down the wrong path with no possibility of return. Furthermore, minor changes or revisions in equipment may require a complete redesign of the FPTA.

Recommendation 12: An expanded research program should be undertaken for JPAs, with emphasis on aids for troubleshooting, to determine

*The comparison was made for aids developed for the UH-1H helicopter under the Vietnamization program. See Ref. 16, pp. 27-28.

which types of troubleshooting aids are most useful to the repairman. Such an effort was initially proposed by AFHRL and should be funded as part of their research program. (See Recommendation 9.)

A promising direction of research has been the development of computer programs to generate FPTAs. These programs can generate optimal, or minimum cost, search paths for equipment that has not yet been built. The potential benefits of these programs are large, even though they generate FPTAs that are successful only 50 percent of the time. Computer-generated aids are cheap and can be used potentially to estimate the level of maintenance required by a specific piece of equipment before its procurement.

Recommendation 13: The further development of computer-generated FPTAs should be supported, and research efforts should be directed toward developing FPTAs that help evaluate the maintenance rates of equipment.

Commercial airlines currently use general job aids. For instance, McDonnell-Douglas, Lockheed, and Boeing have developed job aids for flight-line maintenance on their jumbo jets. The Douglas system, called FEFI/TAFI (Flight Environment Fault Indication/Turn Around Fault Isolation), provides only limited troubleshooting assistance to the flight engineer, but it includes all troubleshooting information in the ground portion of the system. The other airlines apparently use similar systems.

Recommendation 14: DoD should examine commercial aviation troubleshooting systems, such as the FEFI/TAFI system developed by Douglas for the DC-10, for possible military applications.

The Economics of JPAs

The major deterrent to the development of JPAs for new systems is that JPAs cost more than conventional documentation. Rowan⁽¹⁶⁾ cites estimates where JPAs cost up to 25 percent more than conventional documentation.* Since JPAs may differ radically in content and complexity,

* Conventional documentation itself can be quite expensive. McDonnell-Douglas estimated documentation costs for the F-15 to be \$35 million.

the costs must certainly depend on the equipment, the types of JPAs produced, and the specification under which they are produced.

Recommendation 15: DoD should attempt to estimate the incremental cost of several sets of JPAs for various types of electronics systems. These estimates should help determine the cost of preparing JPAs for new systems. The costs should reflect the assumption that the aids would be prepared under the new draft specification TR 73-43 formulated by AFHRL.

A problem exists in relating the level of detail contained in the aids to the level of experience of the user. In principle, more- or less-complicated aids could be developed that would depend on the user's experience. The most-detailed JPAs could be used for trainees and could incorporate additional material for training purposes. (It is interesting to note that studies have shown that job aids are most effective when used by inexperienced personnel; experienced persons may perform as well or even better using conventional documentation.) To help solve this problem, the Navy has developed the concept of a "family" of job aids, that is, a series of JPAs that range from lengthy, very detailed aids for apprentices to more concise material for senior, experienced personnel. One main task for the DoD would be to compare the cost of developing one aid for those at the apprentice level with the cost of developing such a family of aids, which would span all skill levels.

Recommendation 16: In exploring the economic aspects of JPAs, DoD should investigate the cost and potential benefits of developing families of job aids for electronics equipment. These aids would provide appropriate types of assistance to personnel of different skill levels.

Training in Support of JPAs

FPJPAs can improve performance significantly, but a special effort by the DoD and the services will be required to encourage their use by technicians. It has been well established by surveys and observations in the field that technicians frequently do not use available technical orders in carrying out maintenance functions.^(20,21) An educational program aimed at all levels of DoD should be undertaken to develop a

positive attitude toward JPAs and acceptance of the concept. Using the JPA in training would greatly facilitate its acceptance; the technician trained to use JPAs might become dependent on them and would therefore be more likely to use JPAs on the job. Using aids such as maintenance dependency charts in troubleshooting training is particularly important. Researchers feel that these aids have been unsuccessful partly because personnel have not been trained to use them.

Recommendation 17: In those areas where JPAs are introduced, technical training should include instruction in the use of these aids, and incentives should be provided to encourage their use.

Proponents of JPAs have argued that the use of FPJPAs for both troubleshooting and routine maintenance tasks will make it possible to eliminate up to three-fourths of formal technical training. The state of the art in JPAs for troubleshooting tasks has not yet progressed to the point where a wholesale reduction in technical training would be desirable, however. Furthermore, even in those areas where effective FPTAs exist, lengthy technical training may have subtle effects on job performance and motivation which cannot be properly evaluated without substantial operational testing. Until studies are carried out like Project Innovate, proposed by AFHRL, no specific recommendations can be made concerning the reduction of technical school training for electronics maintenance personnel.

Procurement Process and JPAs

As in the case of determining maintenance requirements in general, the procurement process is critical to the proper specification of and use of job aids. In particular, the types of job aids most useful for a particular weapons system and the maintenance manpower training requirements and desired skill level are determined largely by the configuration of the system itself, the built-in test equipment, and the automated ground test equipment available to assist the technician. In some recent systems, such as the Mark II avionics on the F-111, the automatic nature of the built-in test equipment and the ground test equipment have left no useful fault-isolation role for technicians at

the organizational and intermediate levels. Yet this system has been very expensive to maintain, perhaps because of its inability to utilize the judgment of skilled flight-line maintenance personnel. In designing hardware and software components of weapons systems, the capabilities of maintenance personnel aided by JPAs or other forms of documentation need to be explicitly considered. Once the system and its automatic test equipment are designed, its maintenance characteristics and the type of personnel and technical documentation required to maintain the system will be largely determined. If the trend toward built-in test equipment and aerospace ground equipment continues, organizational and intermediate maintenance for avionics will become largely remove-and-replace tasks, which can be performed by relatively unskilled personnel aided by documentation for routine maintenance.

The appropriate JPAs for a weapons system or electronics subsystem should be procured with the system itself. The incremental cost of job aids is less during the procurement process than at a later time, since JPAs will supplant at least some of the conventional documentation purchased during procurement. The subsection on procurement of weapons systems notes that life-cycle costs can be reduced by a prolonged period of operational testing. Research reports on JPAs have noted the necessity of "hands-on" validation of the aids to remove errors. In at least one case (the UH-1H) the original aids were virtually unusable because of errors. It seems reasonable to use the period of operational testing to validate and improve whatever job aids are procured along with the system.

Recommendation 18: JPAs for new weapons systems should be procured at the same time as the system itself. The operational testing period for the new system should be used to validate and revise the JPAs.

One problem in procuring job aids along with the system is that program managers want to reduce procurement costs as much as possible, therefore, job aids are eliminated from the procurement process. Rowan has recommended that the OSD review the technical documentation and funding for new weapons systems and should stimulate innovative approaches and increase funding support for job aids.⁽¹⁶⁾ Foley,⁽²²⁾ in writing

about revised technical documentation for the Air Force, has recommended other far-reaching steps. Foley likens the new concepts in job aids to other systems, primarily hardware in nature, which are also in a developmental stage. He recommends that a special systems project office be created to oversee the development of a revised technical order system which would embody many of the new concepts in job aids. Since this new office would have its own funding, program managers for new weapons systems would not have to allocate resources to the procurement of an upgraded technical documentation system.

Recommendation 19: DoD and the services should seek ways to support the JPA concept in the weapons systems procurement process. For a period of two to three years DDR&E and OSD/I&L should review the specifications and funding for technical documentation for new weapons systems. The services should provide special funding for new types of JPAs within a separate program element.

PERSONNEL AND TRAINING

Since skilled technicians play a key role in the maintenance function, personnel and training policies may have significant impacts on the costs of electronics maintenance. In this section we look specifically at three areas in which these impacts may occur: (1) electronics training, broadly defined to cover on-the-job training as well as technical schooling, (2) assignment of manpower, and (3) the supply of enlistees and reenlistees to electronics maintenance specialties.

Training

Military training can be viewed as the general process by which individuals become proficient at their assigned jobs. This process would, at a minimum, include both formal technical training and the on-the-job training required for initial and subsequent assignments. The efficiency of military training can be evaluated on the basis of the net cost of achieving a given level of proficiency on the job. Although little work has been done in estimating the duration and costs of on-the-job training for electronics specialties, the general opinion is that these costs are considerable and that newly trained personnel

require months of orientation before they can make significant contributions to electronics maintenance.

Initial training for electronics specialists typically lasts for 30 to 40 weeks. Nearly half of this time is devoted to teaching trainees principles of electronics, and the remainder includes developing basic electronics skills and giving training on generic equipment. There are really two questions that arise in seeking ways of reducing formal training costs. The first is whether the lengthy training in electronics principles given to trainees in electronics specialties is justified--especially in view of changes in maintenance practices for recent electronics systems. This question cannot be answered without large-scale demonstrations that could evaluate personnel who have received different amounts of training in electronics theory. Such demonstrations (in conjunction with JPAs) were recommended in the previous subsection in relation to research proposed by AFHRL.

The second question concerns the relevance of training on generic equipment. In some electronics specialties generic equipment is quite typical of equipment encountered in the field, but in other cases the diversity of equipment is such that generic equipment is of no help in preparing a trainee for a field assignment. One Air Force specialty (AFSC 328x4) has responsibility for maintaining 34 different inertial navigation systems; yet a particular technician is effective only on the system for which he has received on-the-job training. Air Force AGE maintenance specialists may be assigned to any of 41 different test stations on 6 different aircraft types. Moreover, recent innovations in AGE may have tended to increase the diversity of maintenance tasks within the electronics area. The existence of unique equipment and the frequent rotation of personnel pose problems for operational commands. A large proportion of maintenance specialists may be undergoing on-the-job training, even when the skill mix reflects considerable seniority. TAC believes that the shortage of experienced personnel is a major problem in maintaining the avionics on the F-111.

Extreme specialization within a military occupation creates a dilemma for the training commands. On the one hand it would be desirable to train personnel on the equipment they would be assigned to in

the field. However, such training may be quite costly in terms of equipment needed and instructors required and would place a heavy burden on the services of accurately projecting assignments for trainees at the time of school assignment. One other alternative is to eliminate the equipment-oriented portion of formal training and provide this training on the job. This would be the simplest and perhaps the most efficient alternative.

Recommendation 20: In fields of electronics specialties, where the equipment is highly diversified, the services should consider increased on-the-job training to replace the instruction given with generic equipment in technical schools.

The existence of an electronics training curriculum which contains substantial amounts of electronics theory has had an influence on other parts of the personnel system. Individuals given technical training must achieve certain aptitude test scores to perform satisfactorily on the electronics theory portion of school training. Moreover, tests that evaluate technical competence for purposes of upgrading personnel after they leave school reflect the types of materials presented in training. To the extent that such materials are not important to job performance, criteria for specialty assignment and upgrading are unduly restrictive.

The training command would benefit from an objective feedback which indicates how well technical school graduates are able to perform their job at various points in time after leaving school. Performance testing would help evaluate changes in training and JPAs and might also identify areas where training is deficient. As was previously suggested in Recommendation 1, in areas where total costs are large, the services should investigate the possibility of administering performance tests on a routine basis to a random sample of its graduates. Performance tests would provide feedback to the training based on actual job capabilities rather than on academic ability.

Personnel

A specialty that maintains highly differentiated equipment requires not only large investments in initial training but in cross-training as

well. One way to begin to reduce cross-training requirements is to keep track of which equipment a given individual can effectively maintain, perhaps simply by adding digits to the occupational identifier. In reassigning or rotating personnel, an attempt could be made to assign journeymen-level personnel to equipment with which they are experienced. In fact, one of the purposes of the Naval Enlisted Classification code (NEC) is to match individuals with particular equipment. The NEC is a four-digit occupational identifier used to supplement the rating. For equipment that is a particular problem to maintain, the service could take further steps and could rotate personnel experienced in maintaining the particular system only to other installations where that system is in use. This would permit them to accumulate experience with the system, which may help improve its maintainability.* The strongest indication that there would be a continued supply of enlistees to electronics, even with reduced formal training, is that the services could, in principle, begin to accept individuals into electronics fields with lower test scores than now required. This could greatly expand the pool of potential enlistees.

Recommendation 21: The military services should reevaluate the military specialty code system in light of the diversity of electronics systems. For electronics specialties that maintain highly diversified types of equipment the services should consider using additional occupational identifiers to indicate which equipment an individual is qualified to maintain. The identifiers can be used in assigning personnel to units. For troublesome electronics systems, this process would ensure that only capable personnel were given responsibility for maintaining a given system; repairmen with the same specialty code but unfamiliar with the particular system would not be rotated in as replacements.

Supply of Military Manpower

Military enlisted personnel are procured through the processes of enlistment and reenlistment. First-term personnel typically enter the

* However, the retention implications of such a policy might make it infeasible for certain types of equipment where all locations are remote or otherwise undesirable.

electronics area by exercising the enlistment option which permits them to choose an area of training. Although the enlistment rate in the electronics area is currently adequate, there is a legitimate question as to whether it would still be adequate if the amount of formal training given to electronics specialists was sharply curtailed. Proponents of JPAs have suggested that much of formal training can be eliminated if well-designed JPAs are widely introduced for electronics maintenance. A second question relating to the supply of electronics personnel concerns retention. Given the problem in maintaining electronics equipment, are reenlistments rates high enough, and if not, what actions can be taken to improve retention in this area?

Definitive answers, of course, cannot be given concerning future enlistment rates, especially if vastly different training policies are in operation. The principal argument that enlistments would be severely restricted is that surveys have shown that a high proportion of enlistees state that training was the most important reason for enlisting. Even if such surveys were reliable, it is not clear whether the trainees' concept of training is limited to formal schooling or whether it includes the attainment of a given level of proficiency in the electronics field. The evidence seems rather to suggest that enlistments may not be that severely affected by reduced formal training.

The question of whether a large proportion of individuals either use or benefit economically from training in the field of electronics is also important. Table 3 shows the distribution of former first-term DoD electronics personnel across selected civilian occupations. These data are compiled from an OASD (M&RA) survey of personnel with less than six years of military service, approximately one year after leaving military service. Only about one-third of employed electronics personnel work in the fields of bench and structural work containing traditional electronics-related jobs, such as electronics repair and electrical installation. Approximately one-fourth of a control group consisting of Army infantry personnel hold jobs in the same area. (These data apply to high-school graduates and do not include those using the "G.I. Bill" to attend college. As a result the figures may overstate differences between electronics and non-electronics personnel.)

Table 3

CIVILIAN OCCUPATIONS FOR EMPLOYED DOD SEPARATIONS (FY 1971)
WITH LESS THAN SIX YEARS OF SERVICE

(Electronics specialists and combat infantry)

Service	Selected Occupations			
	00-05 Professional Scientific	70-79 Bench Work (Incl. Electronics)	80-89 Structural (Incl. Electrical)	Sample Size
High-School Graduates				
Army infantry	0.02	0.05	0.21	1485
Army electronics	0.06	0.07	0.27	1741
Air Force electronics	0.16	0.08	0.24	1023
DoD electronics ^a	0.11	0.08	0.26	3295
College (1-3 years)				
Army infantry	0.09	0.03	0.02	243
Army electronics	0.19	0.07	0.21	637
Air Force electronics	0.22	0.07	0.21	334
DoD electronics ^a	0.21	0.07	0.21	1373

^aArmy, Navy, Air Force. Navy electronics technicians may serve a minimum of six years of service.

The largest differences between electronics and non-electronics personnel occur in the proportion holding professional and scientific jobs, although this difference amounts to less than 10 percent of employed personnel. The picture is somewhat different for college-trained enlisted personnel, but in this group as well as among the high-school educated there may be systematic differences between personnel chosen for electronics training and other personnel. In any event, only a minority of military personnel in the civilian labor force actually use their military training, and this group would be made even smaller if the reenlistee, the student, and the unemployed worker were taken into account.

In short, electronics may be appealing to enlistees as a relatively attractive and challenging military occupation but not for the particular skills acquired by the electronics specialist.

One method of improving the average skill level of military personnel in electronics is by increased retention rates. Within the military, first-term retention rates are traditionally very low, varying over the past decade between 15 and 25 percent. Reenlistment rates in the career force have been in excess of 85 percent within that same period. In fact, military reenlistment rates have been depressed since FY 1967 because of the influence of the Vietnam War and the presence of large numbers of personnel who were motivated to enlist by the threat of the draft. Beginning in FY 1972 the first increases in reenlistment rates could be detected, and it is possible that first-term enlistment rates could return to or surpass the levels of 1960-1965.

Reenlistment rates in the area of electronics have tended to be higher than rates in the military as a whole. (DoD-wide, the first-term reenlistment rate was 30.0 percent for electronics versus 18.6 percent for all other specialties in FY 1972.) This is somewhat surprising in view of the presumed value of electronics training to the civilian sector and because high-aptitude electronics technicians are more likely to be draft-motivated enlistees than other military personnel. Part of the reason for the relatively "high" reenlistment rate for electronics is the relative attractiveness of this type of military specialty, but much of the credit is probably due to the special pay program. Enlisted personnel in electronic specialties qualify for the variable reenlistment bonus (VRB) and for proficiency pay. The VRB pays up to \$8000 for first-term reenlistees, and proficiency pay is an increment to monthly pay ranging from \$50 to \$150. In recent years electronics specialists have qualified for only one-half the maximum VRB payment.* The simplest way to increase reenlistments in the electronics area is to award the maximum amount of special pay to these occupations. This change could be expected to increase reenlistments by a factor of from 1.2 to 1.4.

The Navy has managed to increase its retention of electronics personnel through use of the six-year program. This program provides extra training plus a deferred bonus for men making a six-year commitment.

* The VRB award is based on the manpower requirement for the career force and on an index calculated from the length and cost of military training in the specialty.

The six-year commitment, of course, increases the expected length of service of the first-term enlisted man, but, since the six-year program appeals primarily to career-oriented enlistees, reenlistment rates in this area tend to be significantly higher than in the rest of the Navy. In the four ratings that contain only those obligated for six years, the first-term reenlistment rates ranged from 55 to 90 percent in FY 1972, compared with an overall first-term rate of 23.2 percent. Although the effectiveness of such a program depends on the number of qualified enlistees willing to accept a six-year commitment, the Navy has reportedly been able to fill all of its electronics technician slots with six-year obligors.

Recommendation 22: The military services, particularly the Army and the Air Force, should evaluate the benefits of employing a more senior force of electronics technicians, perhaps by measuring the productivity of personnel with different levels of experience (Recommendation 2). An increased proportion of careerists can be achieved by raising first-term reenlistment rates through increases in special pay or by requiring an extended initial term for personnel serving in the electronics area. This, of course, would raise the average cost per man, but the greater effectiveness of senior personnel in such difficult areas as troubleshooting could result in a requirement for fewer maintenance personnel and thereby could reduce total costs.

III. CONCLUSIONS

In the preceding pages we have presented a conceptual framework and specific recommendations for reducing electronics maintenance manpower costs. As we have pointed out, the question of cost reduction is complex. Areas where improvements can be made in isolation from other parts of the maintenance system are few, if they exist at all, and we have attempted to recognize this interdependency.

Our recommendations can be classified as either (1) ways to reduce the demand for maintenance labor or (2) ways to increase the productivity of maintenance labor. Most of our recommendations and most methods of cost saving lead to improvements in productivity, but a clear distinction must be made between the two possibilities for reducing labor costs. The cost savings result from improvements in labor productivity that are generated by expenditures on non-labor factors of production, such as maintenance aids or training courses. If savings are to be generated, these expenditures will be more than offset by the reduction in the labor force. Cost savings can also be realized from a labor force reduction that does not involve increased expenditures to improve labor productivity. Such improvements would fall into the first classification listed above, where the demand for maintenance labor is reduced. Examples of such changes would be removing unnecessary tasks or implementing organizational changes to take advantage of economies of scale in maintenance. This is the spirit of our recommendations dealing with analyzing comparable civilian activities. These structural changes would, of course, improve labor productivity but would not be the results of investment in labor-saving devices.

To carry out many of our recommendations, timeliness is important--some require immediate action both with respect to research problems and with respect to the implementation of already tested concepts. Other recommendations will have application to the long term. Therefore, to clarify the discussion that follows, the review of recommendations and our related concluding remarks will deal separately with both types of recommendations.

SHORT-TERM DEMONSTRATIONS AND EXPERIMENTS

One of the two principal goals of this report is to recommend demonstrations or experiments that can be undertaken in the short term to help identify ways to reduce personnel and manpower-related costs in electronics maintenance. The preceding sections have identified and recommended eight opportunities for short-term demonstrations or experiments. The short term was defined as approximately the next six months to one year, but even this rather generous interpretation severely limits the number of changes that can be introduced. Whether the subject area is job performance aids, maintenance manpower practices, or maintenance training, creating an experiment or demonstration involves a number of time consuming steps: planning, development, implementation, monitoring, and evaluation. A small-scale demonstration may be just as costly in terms of time as a wholesale innovation.

The strategy adopted here to obtain short-term results has been to start with research already in progress or with innovations already planned, especially since so much time is needed to set up experiments. In the area of maintenance manning practices, this report has emphasized the need to develop cost comparisons between government and contractor depot-level maintenance and between organic and depot electronics maintenance. In particular, the following recommendations were made.

Recommendation 4: Data on the costs of contractor depot repair during the early stages of equipment acquisition of recently developed electronics systems should be compared with regular military depot repair costs where possible. The N-16 and Kearfott-Singer ASN-90 inertial navigators are two systems that might be compared.

Recommendation 5: Comparisons should be made of field and depot retest OK rates and failure rates after repair. These should be used to evaluate the relative diagnostic and repair capabilities at the base and depot levels. The integrated display on the F-111D and inertial measurement set on the A-7D are candidates for study.

with respect to most types of JPAs is to evaluate the impact of these aids in an operational environment. In this regard there are four specific opportunities to begin to acquire field experience with JPAs.

Recommendation 6: The introduction of the PIMO system of job aids for the C-141A should be monitored and evaluated to permit comparisons of maintenance costs and measures of productivity or maintenance efficiency with and without the JPA system. Planning and data collection for monitoring and evaluating the new system should begin immediately.

Recommendation 7: The development of job aids for the AQA-7 sonar subsystem should be followed up with field tests. The Navy should ensure that the field tests are properly conducted, using control groups, collecting data on maintenance costs and performance for the sonar subsystem and on mean times to repair, and collecting other statistics for individual technicians.

Recommendation 8: The decision to cease development of the integrated job aids for the AWG-10 should be reconsidered by the Navy. If

make comparisons of maintenance practices and costs. In particular, DoD should study the Carrousel inertial navigation system developed by General Electric.

In the field of troubleshooting aids DoD may benefit from the new systems developed by McDonnell-Douglas, Boeing, and Lockheed for their jumbo jets.

Recommendation 14: DoD should examine commercial aviation troubleshooting systems, such as the FEFI/TAFI system developed by Douglas for the DC-10, for possible military applications.

THE LONG-RUN PROBLEM OF REDUCING ELECTRONICS MAINTENANCE COSTS

The second principal goal of the report is to develop long-term recommendations relating to the cost of electronics maintenance. The major limitation in achieving efficiency in electronics maintenance is

reliability of statistical estimates. The following career fields should be included: Army, Tactical Electronic Equipment Maintenance (EE) and Air Defense (AD); Navy, Electronics Technician (ET) and Aviation Electronics Technician (AT); Marines, Avionics (62); Air Force, Communications Electronics Support (30) and Avionics Support (32).

Recommendation 2: Research should be undertaken to develop models of military units (where appropriate), to validate the models, and to apply them to the evaluation of manning standards. The possibility of determining manning standards based on data and programs already in existence should be seriously considered. Research should be conducted using simulation models and other methods to develop productivity weights for personnel with differing amounts of experience.

Maintenance of the Existing Inventory

Electronics maintenance costs over the next decade are likely to be dominated by those electronics systems already in the inventory, despite the rapid rate at which the United States develops new weapons systems. Consequently, actions to reduce maintenance costs on existing systems are likely to have a greater impact on cost and performance during the next few years than efforts to procure electronics systems with good maintainability features. In this regard an evaluation of the short-term demonstrations and experiments cited above may have a significant impact on the maintenance of electronics systems. Comparisons of the costs of contractor versus government maintenance and depot versus organic maintenance will provide information on the most useful way to organize the maintenance activity. In addition, an evaluation of operational experience with aids developed for the C-141, the AQA-7 sonar, and the AWG-10 fire control system will also increase our usable knowledge about the efficiency of electronics maintenance activities. These specific examples may provide a good opportunity to develop performance measures and models of the maintenance activity already recommended.

One of the problems with existing electronics maintenance is the great degree of specialization imposed on the technician by the proliferation of electronics components and subsystems. To counteract the

maintenance problems caused by this specialization, the services should move to ensure that personnel have adequate experience with the electronics components they are charged to maintain.

Recommendation 20: In fields of electronics specialties, where the equipment is highly diversified, the services should consider increased on-the-job training to replace the instruction given with generic equipment in technical schools.

Recommendation 21: The military services should reevaluate the military specialty code system in light of the diversity of electronics systems. For electronics specialties that maintain highly diversified types of equipment the services should consider using additional occupational identifiers to indicate which equipment an individual is qualified to maintain. The identifiers can be used in assigning personnel to units. For troublesome electronics systems, this process would ensure that only capable personnel were given responsibility for maintaining a given system; repairmen with the same specialty code but unfamiliar with the particular system would not be rotated in as replacements.

Recommendation 22: The military services, particularly the Army and the Air Force, should evaluate the benefits of employing a more senior force of electronics technicians, perhaps by measuring the productivity of personnel with different levels of experience (Recommendation 2). An increased proportion of careerists can be achieved by raising first-term reenlistment rates through increases in special pay or by requiring an extended initial term for personnel serving in the electronics area. This, of course, would raise the average cost per man, but the greater effectiveness of senior personnel in such difficult areas as troubleshooting could result in a requirement for fewer maintenance personnel and could thereby reduce total costs.

The development of JPAs for routine maintenance tasks, which is well within the state of the art for JPAs, should also be considered as a means of reducing the time required for personnel to learn a new system.

Recommendation 11: Fully proceduralized job performance aids for non-troubleshooting tasks should be considered, especially for maintaining

high-cost equipment now in the inventory. A review should be undertaken to determine if maintenance costs can be reduced significantly

Recommendation 17: In those areas where JPAs are introduced, technical training should include instruction in the use of these aids, and incentives should be provided to encourage their use.

Recommendation 18: JPAs for new weapons systems should be procured at the same time as the system itself. The operational testing period for the new system should be used to validate and revise the JPAs.

The principal area where more work is required to make JPAs operational is in troubleshooting. Troubleshooting aids, particularly fully proceduralized aids, are inherently more complex than aids for routine or "straight-line" maintenance tasks.

Recommendation 12: An expanded research program should be undertaken for JPAs, with emphasis on aids for troubleshooting, to determine which types of troubleshooting aids are most useful to the repairmen. Such an effort was initially proposed by AFHRL and should be funded as part of their research program.

In addition to knowing how well aids work, DoD must also know the cost of procuring various types of JPAs over and above the costs for conventional documentation.

Recommendation 15: DoD should attempt to estimate the incremental cost of several sets of JPAs for various types of electronics systems. These estimates should help determine the cost of preparing JPAs for new systems. The costs should reflect the assumption that the aids would be prepared under the new draft specification TR 73-43 formulated by AFHRL.

Recommendation 16: In exploring the economic aspects of JPAs, DoD should investigate the cost and potential benefits of developing families of job aids for electronics equipment. These aids would provide appropriate types of assistance to personnel of different skill levels.

Electronics Maintenance Costs in Perspective

As we stated earlier in this report, the goal of producing national defense at minimum cost requires simultaneous answers to three broad questions:

1. What quantities and types of weapons systems should be procured?
2. At what level of capability should these systems be maintained?
3. How should the level of maintenance be provided?

Our focus, of course, has been on the third question, with particular emphasis on the implications of past research on JPAs for more immediate action. Larger savings in other areas may be available, but we must address the general question of productivity measurement to make these savings available to DoD.

REFERENCES

1. *The Budget of the United States Government, Fiscal Year 1964*, Executive Office of the President of the United States, Office of Management and Budget, Government Printing Office, Washington, D.C., 1963.
2. *The Budget of the United States Government, Fiscal Year 1974*, Executive Office of the President of the United States, Office of Management and Budget, Government Printing Office, Washington, D.C., 1973.
3. *Final Report of the Defense Science Board Task Force on Electronics Management*, 1973.
4. *Air Force Cost and Planning Factors (U)*, AFM 173-10, United States Air Force, Office of the Comptroller, April 1973 (Confidential).
5. Teng, C., *An Estimating Relationship for Fighter/Interceptor Avionic System Procurement Cost (U)*, The Rand Corporation, RM-4851-PR, February 1966 (For Official Use Only).
6. Cooper, Richard V. L., and Charles Robert Roll, Jr., *The Allocation of Military Resources: Implications for Capital-Labor Substitution*, The Rand Corporation, P-5036, June 1973.
7. *Life Cycle Costing Procurement Guide (Interim)*, LCC-1, Department of Defense, Office of the Comptroller, July 1970.
8. *Casebook Life Cycle Costing in Equipment Procurement*, LCC-2, Department of Defense, Office of the Comptroller, July 1970.
9. Gay, Robert M., *Estimating the Cost of On-the-Job Training in Military Occupations: A Methodology and Pilot Study*, The Rand Corporation, R-1351-ARPA, April 1974.
10. Gay, Robert M., and Gary R. Nelson, "Cost and Efficiency in Military Specialty Training," *Proceedings, Eighth Annual DoD Cost Research Symposium*, November 1973.
11. Fisher, R. R., et al., *The Logistics Composite Model: An Overall View*, The Rand Corporation, RM-5544-PR, May 1968.
12. Ginsberg, A. S., and B. A. King, *Base Operations-Maintenance Simulator*, The Rand Corporation, RM-4072, September 1964.
13. Smith, T. C., *SAMSON: Support-Availability Multi-System Operations Models*, The Rand Corporation, RM-4077-PR, June 1964.
14. Voosen, B. J., *PLANET: Planned Logistics Analysis and Evaluation Technique*, The Rand Corporation, RM-4950-PR, January 1967.
15. *Sortie Rate Analysis (U)*, Director of Plans, DCS Plans and Operations, Headquarters USAF, January 1968 (Secret).
16. Rowan, Thomas C., *Improving DoD Maintenance Through Job Performance Aids*, Information Concepts, Inc., March 1973.

17. Elliott, Thomas K., and Reid P. Joyce, *An Experimental Comparison of Procedural and Conventional Electronic Troubleshooting*, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, AFRL-TR-68-1, November 1968.
18. Weiher, Rodney, and Stanley A. Horowitz, *Formal and On-the-Job Training for Navy Enlisted Occupations*, Institute of Naval Studies, No. 173-71.10, November 1971.
19. Haggstrom, Gus W., *The Role of Experimentation in Manpower Planning*, The Rand Corporation, R-1348-ARPA, December 1973.
20. Folley, John D., Jr., and Thomas K. Elliott, *A Field Survey of Electronic Maintenance Technical Data*, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, AMRL-TR-67-159, November 1967.
21. Serendipity, Inc., *Pimo Final Report: Vols. 1-8*, Space and Missile Systems Organization, Air Force Systems Command, Norton Air Force Base, May 1969.
22. Foley, John P. Jr., "A Proposed Modified Technical Order System and Its Impact on Maintenance, Personnel and Training," Air Force Human Resources Laboratory, draft, November 1973.
23. *Selected Manpower Statistics*, Department of Defense, April 1973,

SELECTED BIBLIOGRAPHY: JOB PERFORMANCE AIDS

- Adams, W. H., and H. Bayer, *Maintenance Fault Isolation in the 1970s*, Sixth Annual FAA International Aviation Maintenance Symposium, Oklahoma City, Oklahoma, December 1970.
- Booher, Harold R., *Research Technique for Evaluating Information Presentation Methods*, Paper presented at Equipment Manuals Symposium, Washington, D.C., October 1972.
- Chalupsky, Albert B., and Thomas J. Kopf, *Job Performance Aids and Their Impact on Manpower Utilization*, EDL-TR3276, Philco Corporation, Palo Alto, California, May 1967.
- Elliott, Thomas K., *A Comparison of Three Methods for Presenting Procedural Troubleshooting Information*, AMRL-TR-66-191, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, April 1967.
- , and Reid P. Joyce, *An Experimental Comparison of Procedural and Conventional Electronic Troubleshooting*, AFRL-TR-68-1, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, November 1968.
- Foley, John P., Jr., *Job Performance Aids Research Summary and Recommendations*, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, April 1969.
- , *Task Analysis for Job Performance Aids and Related Training*, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, April 1969.
- , *Description and Results of the Air Force Research & Development Program for the Improvement of Maintenance Efficiency*, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, September 1972.
- , *A Proposed Modified Technical Order System and Its Impact on Maintenance, Personnel and Training*, Air Force Human Resources Laboratory, draft, November 1973.
- Folley, John D., Jr., and Thomas K. Elliott, *A Field Survey of Electronic Maintenance Technical Data*, AMRL-TR-67-159, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, November 1967.
- Gebhard, Richard M., *Development of a Training Program and Job Aids for Maintenance of Electronic Communication Equipment*, Human Resources Research Organization, HumRRO TR-70-19, Alexandria, Virginia, December 1970.

Horn, Leon, *Job Performance Aid Test*, Naval Weapons Engineering Support Activity, Washington Navy Yard, Washington, D.C., November 1972.

Development of a Procedure-Oriented Training Program for HAWK Radar Mechanics, Human Resources Research Organization, HumRRO TR-69-25, Fort Bliss, Texas, December 1969.

Krohn, C. A., et al., *Evaluation of Simms for An/SRC-20 Radio Set*, Research Triangle Institute, Research Triangle Park, N.C., November 1971.

Ostrominski, John, *Initiatives for Reducing Personnel and Maintenance Costs with Job Performance Aids*, Maxwell Air Force Base, Alabama, February 1972.

An Industry Study of the Use of Technical Orders in Support of Flight Line Maintenance, National Security Industrial Association (NSIA), Washington, D.C., June 1972.

Post, Theodore J., *Advanced Manpower Concepts for Sea-Based Aviation Systems (AMSAS)*, Serendipity, Inc., Arlington, Virginia, December 1970.

-----, and Harold E. Price, *Development of Innovative Job Aid Concepts: Volume I--Description of Concepts*, Naval Air Systems Command, Arlington, Virginia, May 1972.

Price, Harold E., et al., *Development of Information Measurement Techniques for Quality Assurance of Navy Aircraft Maintenance Job Aids: Part 1, Research and Development Effort*, Naval Air Systems Command, Arlington, Virginia, June 1971.

Rogers, James P., and Walter H. Thorne, *The Development and Evaluation of Improved Troubleshooting Manuals*, Human Resources Research Organization, Fort Bliss, Texas, April 1963.

Rowan, Thomas C., *Improving DoD Maintenance Through Job Performance Aids*, Information Concepts, Incorporated, March 1973.

Serendipity, Inc., *Pimo Final Report: Vol. 1-8, Space and Missile Systems Organization*, Air Force Systems Command, Norton Air Force Base, California, May 1969.

Shriver, Edgar L., et al., *A Description and Analytic Discussion of Ten New Concepts for Electronics Maintenance*, Human Resources Research Organization, Alexandria, Virginia, December 1966.

-----, *Determining Training Requirements for Electronic System Maintenance, Development and Test of a New Method of Skill and Knowledge Analysis*, Human Resources Research Organization, Alexandria, Virginia, June 1960.

-----, Dennis C. Fink, and Robert C. Trexler, *FORECAST Systems Analysis and Training Methods for Electronics Maintenance Training*, The George Washington University, Human Resources Office, Alexandria, Virginia, May 1964.

Stenner, A. B., and J. H. Robinson, *Algorithms--The Transfer of Experience to Newly Trained Men: Electronic and Radio Technician*, Vol. 4, No. 4, January 1970.

Phase I--Project Faate Final Report, Product Support Equipment Department, Westinghouse, Maryland, June 1967.

USATECOM, *Final Report of Test of Audio Visual Information System*, White Sands Missile Range, New Mexico, November 1964.

SELECTED BIBLIOGRAPHY: SYSTEMS ACQUISITION STUDIES

- Alexander, Arthur J., *R&D in Soviet Aviation*, The Rand Corporation, R-589-PR, November 1970.
- Harman, A. J., and Susan Henrichsen, *A Methodology for Cost Factor Comparison and Prediction*, The Rand Corporation, RM-6269-PR, August 1970.
- Klein, B. H., T. K. Glennan, Jr., and G. H. Shubert, *The Role of Prototypes in Development*, The Rand Corporation, RM-3467/1-PR, April 1971.
- , et al., *Military Research and Development Policies*, The Rand Corporation, R-333, December 1955.
- Nelson, Richard R., *The Economics of Parallel R&D Efforts: A Sequential-Decision Analysis*, The Rand Corporation, RM-2482-PR, November 1959.
- Peck, Merton J., and Frederic, Scherer, *The Weapon Acquisition Process*, Harvard University Press, Cambridge, Mass., 1962.
- Perry, Robert, *A Dassault Dossier: Aircraft Acquisition in France*, The Rand Corporation, R-1148-PR, September 1973.
- , *Innovation and Military Requirements: A Comparative Study*, The Rand Corporation, RM-5182-PR, August 1967.
- , et al., *System Acquisition Experience*, The Rand Corporation, RM-6072-PR, November 1969.
- Smith, Donavon F., "Development Planning: A Link Between Requirements and Systems." *Air University Review*. 22. No. 1. November/December

